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CONTENTS

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MONTHLY WEATHER REVIEW

First published in 1872, the Monthly Weather Review serves as a medium of publication for technical contributions in the field of meteorology, principally in the branches of synoptic and applied meteorology. In addition each issue contains an article descriptive of the atmospheric circulation during the month over the Northern Hemisphere with particular reference to the effect on weather in the United States. A second article deals with some noteworthy feature of the month's weather. Illustrated. Annual subscription Domestic, $3.50; Foreign, $4.50. Subscription to the *Review* does not include the *Supplements* which have been issued irregularly and are for sale separately.

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(Continued on inside back cover)

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The printing of this publication has been approved by the Director of the Bureau of the Budget, February 11, 1952

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ANALYSIS OF WINDS, WIND WAVES, AND SWELL OVER THE SEA TO THE EAST OF JAPAN DURING THE TYPHOON OF SEPTEMBER 26, 1935

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ABSTRACT

An analysis of winds, wind waves, and swell over the sea to the east of Japan during the historical typhoon of September 26, 1935, is given. Occurrence of the storm and its movement across a main squadron of the Imperial Japanese Fleet which was then conducting grand maneuvers provided what may be the best coverage on record of surface winds, wind waves, and swell within 200 nautical miles of a typhoon center in its mature stage, and furnished an unequaled set of data for studying the relation between the meteorological and oceanographical elements over the ocean during a period of hurricane winds.

INTRODUCTION

For a number of years, the Hydrographic Department, Imperial Japanese Navy, kept secret the meteorological observations [1, 2, 3] on winds, wind waves, and swell over the sea to the east of Japan during the historical typhoon of September 26, 1935. The Hydrographic Department prepared a report in 1937 [1] that contained fairly good descriptions, tabulations, and a set of successive maps illustrating the pressure patterns, the field of wind speed (isovels) and lines of constant wave heights through the period 0600 to 1800 JMT of the 26th. The current report is intended to present pertinent extracts from this report and further intermediate studies, with the hope that they may be of assistance in establishing a firmer understanding of the dynamics of a typhoon in its mature stage.

MOVEMENT OF TYPHOON ACROSS THE FLEET

On September 16, 1935, the Central Meteorological Observatory, Tokyo, discovered evidence of a tropical disturbance in the formative stage in the sea northwest of the island of Saipan. It soon increased to typhoon force and moved slowly on a variable northerly course. The course turned more to north-northeast as the typhoon moved through western Japan on the 25th. After leaving the West Japan area, the center continued a north-northeasterly course, crossed over the Sea of Japan, and dissipated as it moved to sea to the west of Hokkaido.

Long before the first typhoon dissipated, the next tropical disturbance developed in the sea east-northeast of Saipan on September 20. This new typhoon moved on a northwesterly course, and thence curved northward, its intensity increasing to typhoon force. At 0300 JMT, September 26, the S. S. *Ogura-maru* reported hurricane winds 29 to 35 m. sec.$^{-1}$ (56 to 68 knots) from the southeast, and falling pressure of 732.5 mm. of Hg. (977 mb.) near the center. The typhoon finally moved on a north-northeasterly course at the speed of about 70 to 80 km. hr.$^{-1}$ (38 to 43 knots) and passed over sea to the east of Japan in its mature stage. Thus it completed its full cycle of development in the open sea and never passed over Japan proper. Table 1 shows the central pressure, the track, and the velocity of movement of this second typhoon.

TABLE 1.—*Central pressure, track, and velocity of the typhoon center, Sept. 21–27, 1935.* (From the *Geophysical Review* for September 1935 [3])

Date and hour (135th meridian civil time)	Central pressure (estimated) mm. Hg. (mb.)	Locus of center		Movement of center	
		Lat.° N.	Long.° E.	Direction	Speed km/hour (knots)
Sept. 21, 06h		17	150	W	7 (4)
Sept. 22, 06h		17	148	W-NW	7 (4)
Sept. 23, 06h		18	147	NNW	9 (5)
Sept. 24, 06h		20	146	NNW	19 (10)
Sept. 25, 06h		25	144	NNW-N	46 (25)
Sept. 26, 06h	718 (957)	36	143	NNE-NE	73 (39)
Sept. 27, 06h		50	155	N	85 (46)

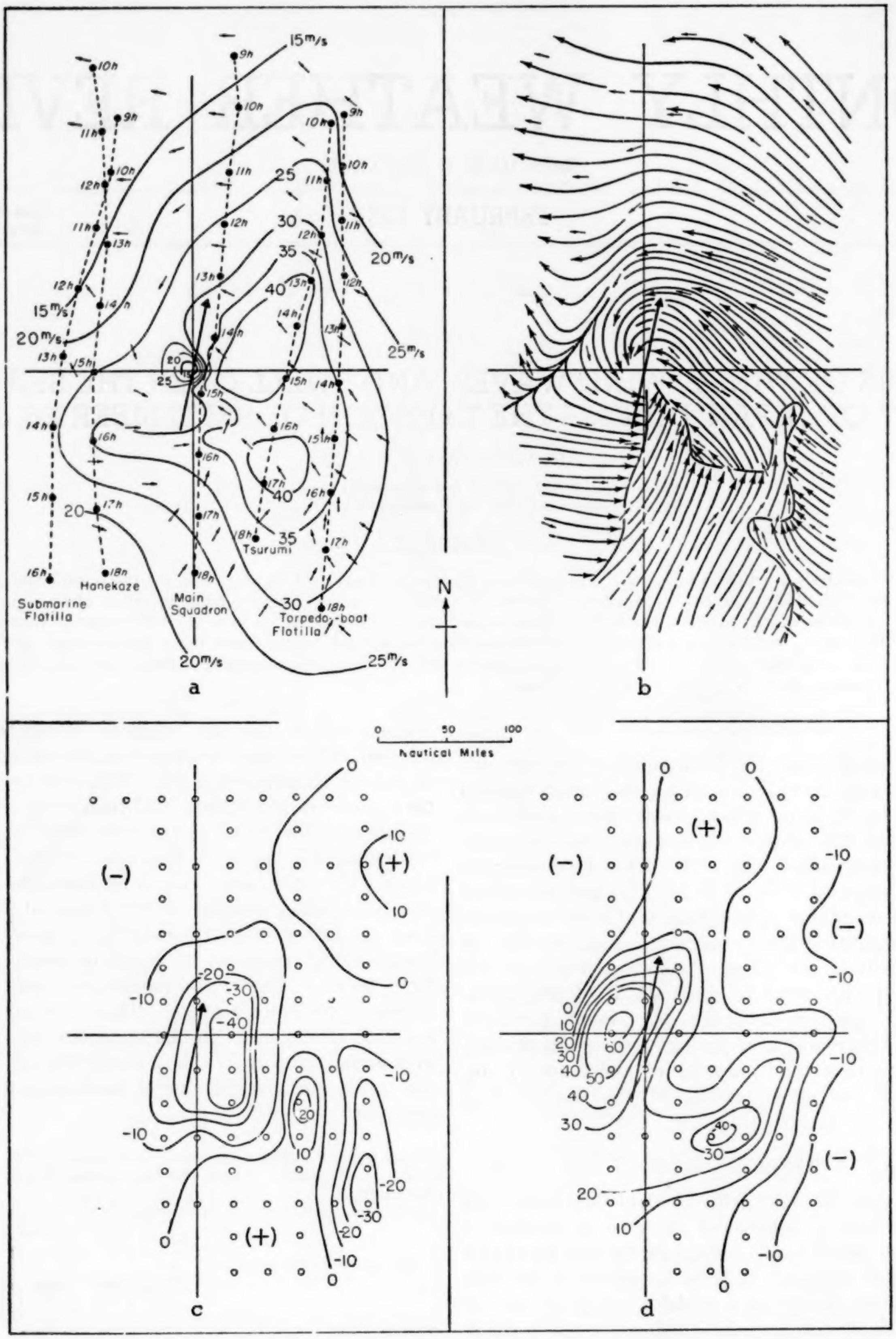

FIGURE 1.—Composite charts of the typhoon, September 26, 1935. Intersection of cross-lines represents the center of pressure symmetry. The heavy arrow through the center indicates the direction of movement of the typhoon. (a) Chart of wind speeds and directions in the typhoon. Small arrows represent the wind directions: isovels (lines of constant wind speeds) are drawn for each 5 m. sec.$^{-1}$ Dots are positions of naval units at hourly intervals (JMT). (b) Streamline patterns over the same area. (c) Horizontal divergence field computed from the wind field for the storm. Small circles indicate positions where computations were made. To obtain horizontal divergence, multiply the indicated values by m. sec.$^{-1}\times$(50 nautical miles)$^{-1}$ or 1.1×10^{-5} sec.$^{-1}$ (d) Vorticity field computed from the wind field for the storm. Small circles indicate positions where computations were made. To obtain vorticity, multiply the indicated values by m. sec.$^{-1}\times$(50 nautical miles)$^{-1}$ or 1.1×10^{-5} sec.$^{-1}$

As it advanced north-northeastward, the typhoon center crossed over the RED 4th Imperial Japanese Fleet shortly after noon of September 26. Figures 2 (inset) and 6 show the path of the typhoon through the maneuvering area. Figure 1a shows the movement of the various naval units relative to the center of the typhoon. The general path of the main squadron, the torpedo-boat flotilla, the submarine flotilla, the transport ship *Tsurumi*, and the destroyer *Hanekaze* relative to the storm shows that a fairly dense net was available to obtain successfully a good number of observations from the storm area. Occurrence of the storm and its movement across the main squadron provided what may be the best coverage on record of surface winds, wind waves, and swell within 200 nautical miles of a typhoon center. Simultaneous observations of wave height during the course of the storm furnished an unequalled set of data for relations between the meteorological and oceanographical elements over the ocean during a period of strong winds.

The observation of the second typhoon was especially noteworthy for the following three interesting features. (1) The storm kept to the open sea in a mature stage. (2) The storm center crossed over a main squadron of the Imperial Japanese Fleet[1] which was then conducting grand maneuvers. (3) The net of meteorological observations was fortunately fairly dense. These observations have made it possible to construct a more complete picture of the structure of a typhoon in its mature stage than has been possible before.

METEOROLOGICAL OBSERVATIONS

When the center reached the main squadron at 1420 to 1435 JMT, the minimum pressure was recorded as follows:

Warship	Minimum pressure	Date and hour (135th) meridian civil time
Haguro	719.3 mmHg (959 mb)	Sept. 26, 1418
Hôshô	722.0 (963)	1420
Ryuzyo	718.2 (958)	1420
Ashigara	721.8 ? (962)	1425
Myôkô	720.5 ? (961)	about 1425
Nachi	720.5 (961)	1430
Mogami	719.6 (959)	1435
Mikuma	719.6 (959)	1435

The barometric readings from the mercury barometer (marine type) on the Warship *Nachi* were taken for every five consecutive minutes, and are considered to be most reliable. The observations of wind speeds and directions by means of cup anemometers were available for each group of the units indicated in figure 1a. The mean (over 20-minute periods) wind speeds calculated from these data are tabulated in table 2.

It must be kept in mind, however, that the progressive movement of the storm was very large (more than 70 km $hr.^{-1}$) and the latitude was rather high (about 40° N.). Therefore the storm was not circular or symmetrical with respect to its center of pressure. The "eye" was 8 to 9 nautical miles in radius. The field of winds suggests the formation of fronts in the vortex as it moved into the middle latitudes. The streamline patterns shown in figure 1b exhibit a pronounced similarity to Shaw's representation of the air currents in a cyclone [4]. The horizontal divergence field and the relative vorticity field for the storm computed *from the wind field* are shown in figures 1c and 1d. The values for the horizontal divergence and the vorticity are in meters per second per 50 nautical miles, or 1.1×10^{-5} $sec.^{-1}$ The singularity in the eye of the storm has been disregarded in figure 1c in order to avoid complications. It might be pointed out that the vorticity corresponding to the Coriolis parameter at the latitude in question (about 40° N.) has an approximate value of 0.93×10^{-4} $sec.^{-1}$

From table 2, we can see that the wind speeds were much greater in the right half than in the left half of the typhoon.

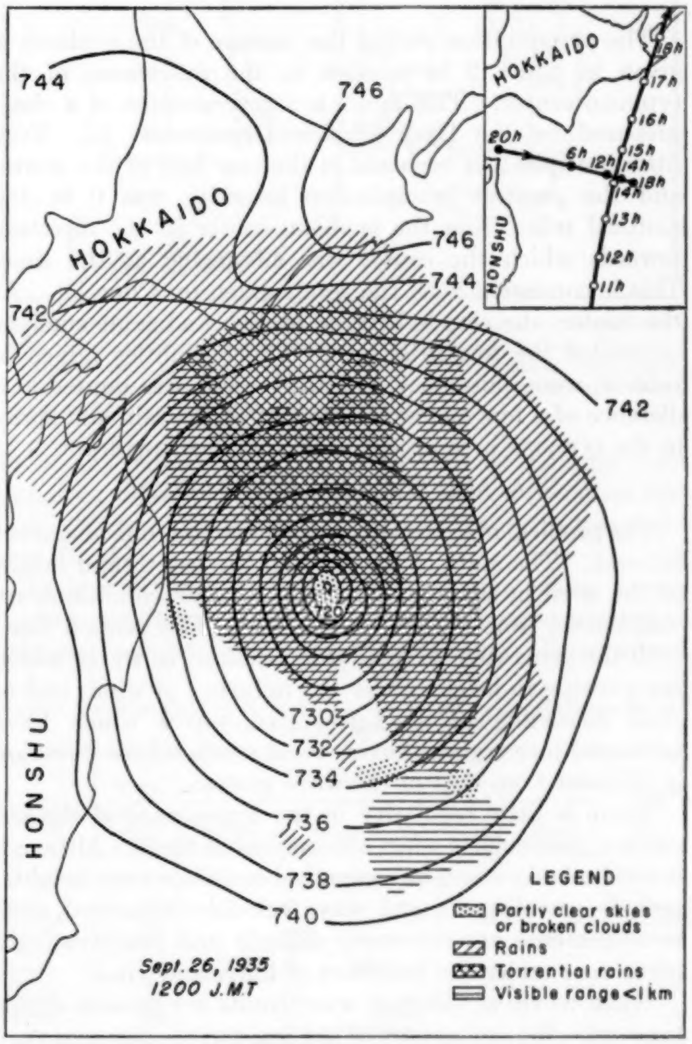

Figure 2.—Pressure pattern over the sea to the east of Japan at 1200 JMT, September 26, 1935. Isobars are drawn for each 2 mm. of Hg. (about 2.7 mb.). Shading indicates composite distribution of rains, torrential rains, and poor visibilities (< 1 km.) relative to the center of the typhoon. The inset (upper right) shows the path of the typhoon center during the critical period from 1100 to 1800 JMT, September 26, and the trajectory traversed by the main squadron from 2000 JMT, September 25 to 1800 JMT, September 26.

[1] The bows of two destroyers, *Hatsuyuki* and *Yûgiri*, were broken off as a result of excessive storm waves, and many officers and sailors were lost. Arakawa, one of the authors, was then a forecaster of the Central Meteorological Observatory, Tokyo, and was vitally concerned with this typhoon.

TABLE 2.—*The mean (over 20 minute periods) wind speeds (m/sec.) for each group in the fleet, Sept. 26, 1935*

	Submarine flotilla	*Hanekaze*	Main squadron	*Tsurumi*	Torpedo-boat flotilla
Name of warships, etc.	Mean values from this flotilla.	*Hanekaze*	*Ashigara*, *Sendai*, *Taigei*, *Myōkō*, *Nachi*, *Haguro*, *Mogami*, *Mikuma*, *Kitakami*, *Kiso*, *Ooi*, *Tenryu*, *Ryuzyo*, *Hōshō*, *Kamui*	*Tsurumi*	Mean values from this flotilla.
06h			13.5	12	11.6
07h			12.8	13	14.1
08h			12.5	17	16.2
09h	6	8	13.7	18	17.9
10h	6	10	16.4	22	19.1
11h	6	10	21.1	27	23.7
12h	9	11	25.3	30	27.3
13h	10	15	29.8	41	32.3
14h	8	18	32.5	42	35.0
About 14h 30m			[1] 34.5		
15h	7	25	31.5	40	36.0
16h	10	30	31.5	38	35.1
17h	5	20	26.3	40	32.3
18h	2	19	23.5	33	29.8
Remarks	The center passed about 100 nautical miles east of this flotilla.	The center passed about 75 nautical miles east of this destroyer.	The center moved through the main squadron at about 1430 JMT. The radius of the calm area with partial clearing was approximately 8 nautical miles.	The center passed about 70 nautical miles west of this destroyer.	The center passed more than 100 nautical miles west of this flotilla.
	In the left half of the typhoon			In the right half of the typhoon	

[1] Maximum mean.

The precipitation during the passage of the typhoon is given in figure 2 in relation to the movement of the typhoon center. This figure is a reproduction of a chart prepared by the Hydrographic Department [1]. Very little precipitation occurred in the rear half of the storm, and the greatest precipitation intensity was 0 to 180 nautical miles from the typhoon center in the direction towards which the center was advancing at the time. This is consistent with the result given by Cline [5]. At the center, the clouds became broken and faint sunlight succeeded the torrential rain. The visibilities (given in table 3) were quite poor and the horizon was limited at a distance of a few meters on account of the rain and spray in the typhoon area except in the left rear quadrant.

SEA AND SWELL OBSERVATIONS

The problem of forecasting sea and swell is one of current interest. The state of the sea and the length and height of the swell in the open sea under stormy conditions are well-known from various authorities. This section deals with the generation of *wind waves* defined as waves which are growing in height under the influence of wind, and of *swell* consisting of wind-generated waves which have advanced into regions having local winds whose direction is different from that of the wave motion.

There is little regularity in the appearance of the sea surface, particularly when a stormy wind blows. Although individual waves can be recognized and their wave heights, periods, wavelengths, and wave velocities measured, such measurements are extremely difficult and comparatively inaccurate under the condition of hurricane winds.

When waves of different wave fronts are present simultaneously, the appearance of the free surface becomes very complicated. At some points the waves are opposite in phase and therefore tend to eliminate each other, whereas at other points they coincide in phase and reinforce each other. If interference occurs, waves may attain the critical steepness 1/7 and break [6, 7].

The strong easterly winds in the right front quadrant of the typhoon showed considerable uniformity and as a consequence of their continued blowing from the east, the corresponding wind waves were relatively large. For an observer standing initially in the right front quadrant of the typhoon, the wind direction would shift suddenly from southeast to south or southwest as the typhoon center moved northward. Thus in the right rear quadrant new waves were formed, receiving energy from the south or southwest winds. Over the ocean in the right rear quadrant, the seas were then unusually pyramidal, mountainous, and confused. These pyramidal storm waves resulted in considerable damage to the Imperial Japanese 4th Fleet on September 26, 1935.

The wind waves as related to the movement of the typhoon, during the passage of the storm over the main squadron, the torpedo-boat flotilla, the submarine flotilla, the transport ship *Tsurumi* and the destroyer *Hanekaze* are given in figure 3 (a reproduction of a chart prepared by the Hydrographic Department). The state of the sea reported according to the sea scale (see below) is also tabulated in table 4. It is clear that the wave heights were the greatest in the right rear quadant of the

TABLE 3.—*Visible ranges in the typhoon area, Sept. 26, 1935*

Time (135th meridian civil time)	*Hanekaze* (in visibility scale)	Main squadron (in km.)	*Tsurumi* (in visibility scale)	Torpedo-boat flotilla (in km.)
6h	6	3.3	2	6.5
7h	6	2.0	2	8.2
8h	7	1.9	2	7.8
9h	10	1.8	2	7.0
10h	3	1.5	1	4.0
11h	3	1.0	1	2.7
12h	3	.9	0	1.7
13h	2	.6	0	1.1
14h	2	.5	0	.9
15h	2	.9	0	1.1
16h	6	.8	0	1.1
17h	6	.8	0	1.2
18h	5	1.8	0	1.2
	In the left half of the typhoon.		In the right half of the typhoon.	

TABLE 4.—*State of the sea (according to the sea scale) in the typhoon area, Sept. 26, 1935*

Time (135th meridian civil time)	Main squadron	In the right half (torpedo-boat flotilla)
0600	4.3	4.7
0800	4.3	4.8
1000	5.1	5.6
1100	5.8	6.4
1200	6.7	7.0
1300	7.2	7.9
1400	7.7	8.2
1500	8.3	8.5
1600	8.5	8.4
1700	8.8	8.4
1800	8.3	8.2
1900	8.2	8.0

typhoon. The heights of wind waves as shown in figure 3 may be a little large in view of the values given in table 4. However it is possible that this chart represents extreme values whereas those in table 4 are average heights. The wind forces corresponding to the code figures of the sea scale are indicated below:

Sea scale code figures	*General description*	*Wind force equivalent (in Beaufort number)*	*Wave height equivalent (in meters)*
0	Dead calm	0	0
1	Very smooth	1	<0.3
2	Smooth sea	2–3	0.3– 0.6
3	Slight sea	4	0.6– 1.0
4	Moderate sea	5	1.0– 1.5
5	Rather rough sea	6	1.5– 2.5
6	Rough sea	7	2.5– 4.0
7	High sea	8–9	4.0– 7.0
8	Very high sea	10	7.0–13.0
9	Phenomenal or precipitous sea	11–12	>13.0

The state of the sea is shown more clearly in table 5 which gives measured height, length, velocity, and period for the highest waves. Classical theory on surface waves indicates that velocity c, wave length L, and period T for deep-water waves which do not involve a bodily transfer of water, are interrelated by the formulas [6, 7]

$$c=\sqrt{gL/2\pi}=gT/2\pi, L=2\pi c^2/g=gT^2/2\pi, T=\sqrt{2\pi L/g}=2\pi c/g.$$

With c in m. sec. $^{-1}$, L in meters, and T in seconds:

$$c=1.25\sqrt{L}=1.56T, L=0.641c^2=1.56T^2, T=0.801\sqrt{L}=0.641c.$$

Thus, if one characteristic quantity is measured the other two can be computed, and if two or three are measured the correctness of the theory as applied to ocean waves can be checked.

Table 6 shows that comparisons of measured and computed values for the *Mikuma* gave rather unsatisfactory results. This may indicate that the state of the sea as observed by the main squadron was, to some extent, uncertain. Comparisons of measured and computed values for the wavelength and the wave period from the cruiser *Nachi* on the other hand gave fairly satisfactory results.

After Sverdrup and others [6, 7], the steepness defined by the ratio of the wave height, H, and the wavelength,

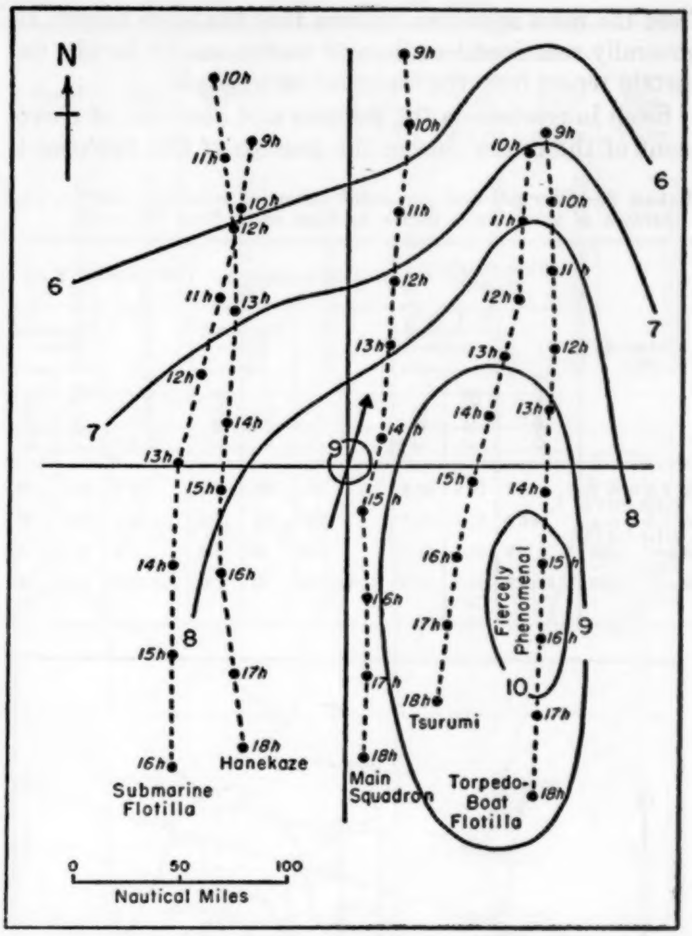

FIGURE 3.—Composite chart showing the state of the sea in the typhoon of September 26, 1935. Intersection of the cross lines represents the center of the typhoon. The arrow through the center indicates the direction of movement of the typhoon. Dots indicate positions of naval units at hourly intervals (JMT). Lines of constant wave heights are drawn for each unit of the sea scale (see scale table in text).

L, has the critical value 1/7. Observations from the main squadron confirm that the ratio H/L always remained less than 1/7 except for the uncertain report from the transport ship *Susaki*.

As is well known, the heights of large waves under stormy conditions are generally overestimated and wave heights above 20 meters are extremely rare. Observations

TABLE 5.—*The state of the sea observed by the main squadron in the typhoon area, Sept. 26, 1935*

Name of ship	Time (135th meridian civil time)	Highest waves				Steepness H/L (computed)
		Height H (meters)	Wave length L (meters)	Wave velocity c (m/sec)	Period T (second)	
Hôshô	1215	10				
Mikuma	1250	8	180	14.3	13.0	1/23
Hôshô	1400	14				
Hôshô	1420	18				
Haguro	1418	15	About 350			1/23
Mikuma	1445	10	200	14.3	13.3	1/20
Amagiri	1458	25	300			1/12
Asakaze	1500	>15	200~300 (estimated)			1/13~1/20
Nachi	1500	13~14	120	9	9	1/9
Tsurumi	1500	>10	About 200			1/20
Naka	1522	14 (pyramidal)				
Susaki	1540	20~30	150			1/8~1/5
Nachi	1550	13~14	About 120	About 8	About 9	1/9

from the main squadron confirm that the wave height, H, generally remained less than 20 meters except for the uncertain report from the transport ship *Susaki*.

Swell in relation to the position and direction of movement of the center during the passage of this typhoon is charted in figure 4, which is also a reproduction of a chart prepared by the Hydrographic Department. The swell of greatest intensity also occurred in the right rear quadrant.

TABLE 6.—*Observed and computed values of velocities, lengths, and periods of wind waves in the typhoon area, Sept. 26, 1935*

Name of ship	Wave velocity c, m. sec.$^{-1}$			Wave length L, m.			Wave period T, sec.		
	Observed	Computed from—		Observed	Computed from—		Observed	Computed from—	
		$1.25\sqrt{L}$	$1.56T$		$0.641c^2$	$1.56T^2$		$0.801\sqrt{L}$	$0.641c$
Mikuma (1250 JMT).	14.3	16.8	20.3	180	131	264	13.0	10.7	9.2
Mikuma (1445 JMT).	14.3	17.7	20.7	200	131	276	13.3	11.3	9.2
Nachi (1500 JMT).	9	13.7	14.0	120	52	126	9	8.8	5.8
Nachi (1550 JMT).	About 8	13.7	14.0	About 120	41	126	About 9	8.8	5.1

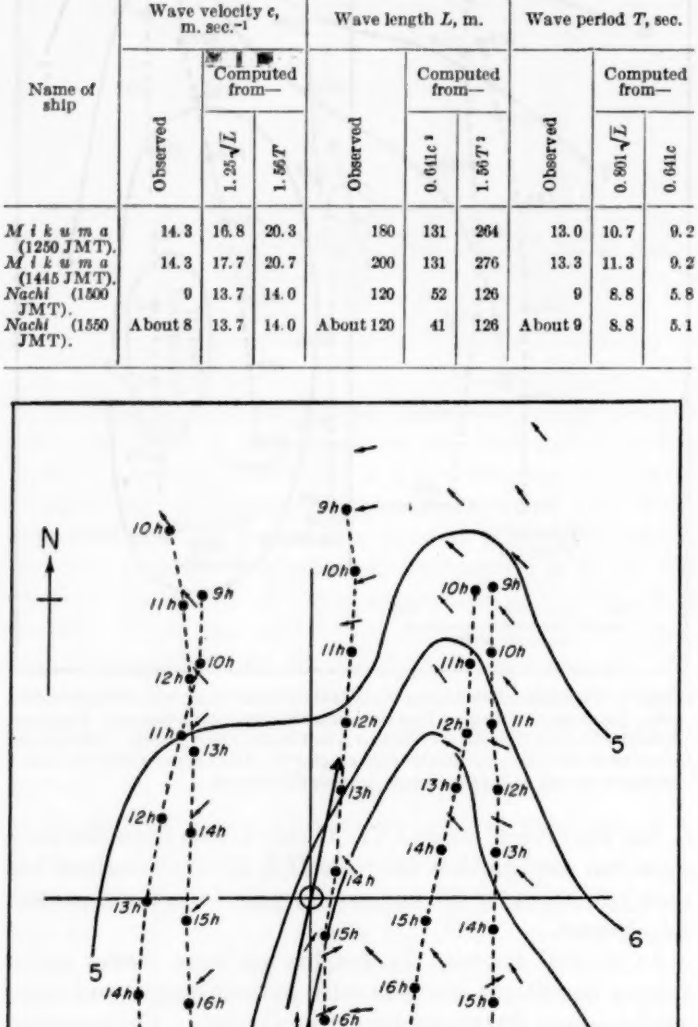

FIGURE 4.—Composite chart showing swell in the typhoon of September 26, 1935. Intersection of cross lines represents the center of the typhoon. The heavy arrow through the center indicates the direction of movement of the typhoon. Dots indicate positions of naval units at hourly intervals (JMT). Small arrows show the directions of swell. Lines of constant swell character are drawn for each unit of the swell scale.

The state of the pyramidal sea in the right rear quadrant (1520 JMT) was photographed by Lieut. G. Matsuura looking to the windward on board the Cruiser *Nachi*. Because the quality of the photograph is too poor for reproduction, the behavior is illustrated schematically in figure 5. Tannehill [8] showed the deviation of wind to the left of the swell in the Northern Hemisphere; that is, the observer standing with his *back* to the wind would find the swell moving off to the right. Figure 5 shows clearly the opposite case; that is, the observer standing with his *face* to the southwest strong wind found the swell moving off to his right within this limited area; i. e., in the right rear quadrant.

The rolling and pitching of ships are of course a function of the winds, the state of the sea, and the characteristics of ships. They can hardly be analyzed therefore in a simple manner. The maximum amplitudes of the rolling, in degrees, are tabulated in table 7 for reference. These angles are the total angle of roll from port to starboard.

Figure 6 portrays the path of the typhoon center during the critical period of 1100 to 1700 JMT of September 26, and the trajectory traversed by the main squadron during the period of 2000 JMT of the 25th to 1800 JMT of the 26th. The thin full lines are lines of constant sea depth

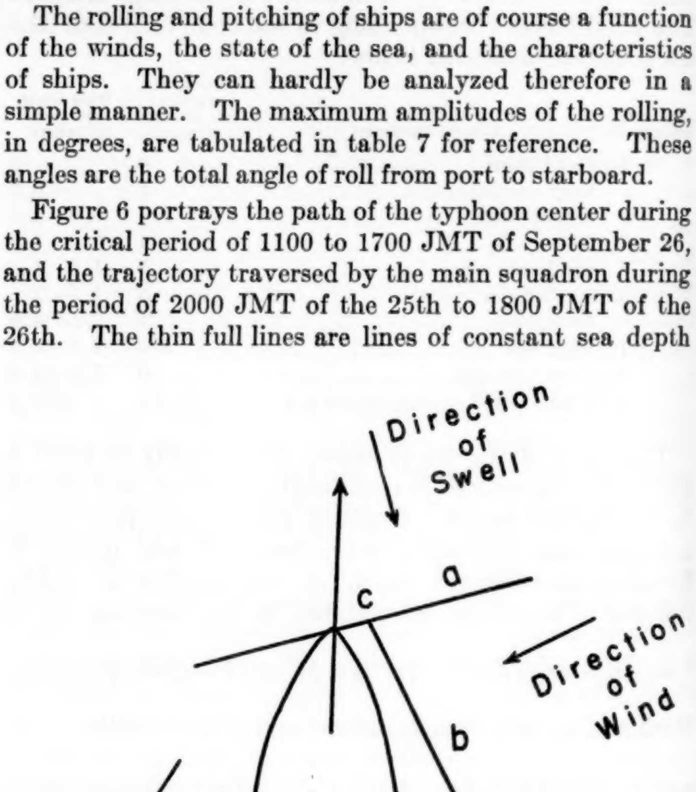

FIGURE 5.—Schematic illustration of the behavior of the sea in the right rear quadrant (1520 JMT) of the typhoon of September 26, 1935. Based on photographs by Lieut. G. Matsuura, looking to the windward on board the cruiser *Nachi*. The direction of movement of the cruiser was 15 on the 36-point direction scale. a indicates the wave front of swells from the southeast; b, the wave front of wind waves under the influence of wind of speed 27 m. sec.$^{-1}$ and direction 21; c, pyramidal waves. Note the deviation of the wind to the right of the swell, a marked exception to Tannehill's rule [8].

TABLE 7.—*Greatest amplitude of the rolling of the ships from port to starboard in degrees, Sept. 26, 1935*

Time (135th meridian civil time)	In the left half of the typhoon: *Hanekaze*	*Ashigara Myôkô Nachi Haguro*	*Mogami Mikuma*	*Kitakami Ooi Kiso Sendai*	*Ryûzyô*	*Hôsyô*	*Tenryû*	*Taigei*	*Kamui*	In the right half of the typhoon: *Tsurumi*	*Kinu Naka*	Extra class destroyer	*Tsuki* class destroyer	*Kaze* class destroyer
0600	6	8	8	9	15	11	25	7	57	14	16	16	16	18
0700	6	8	8	10	13	11	30	7	32	13	14	18	17	18
0800	6	8	9	11	18	10	28	6.5	32	15	12	20	19	23
0900	8	8	9	12	20	11	24	7	20	16	14	22	17	25
1000	12	8	10	14	20	10	33	25	27	16	23	24	22	27
1100	10	10	11	13	20	10	25	35	23	18	29	27	29	35
1200	22	9	15	13	13	26	20	45	31	20	21	34	39	53
1300	27	15	18	18	13	15	45	60	24	32	44	53	56	53
1400	30	22	24	28	21	31	65	75	48	24	60	54	64	58
1500	38	23	24	25	18	41	68	100	58	30	47	67	75	67
1600	44	22	25	30	19	27	37	73	53	34	42	68	69	69
1700	50	22	26	31	18	26	32	55	48	34	52	69	68	70
1800	49	19	26	24	28	15	30	55	45	30	60	65	64	62

drawn for each 1,000 meters. They indicate that wind, waves, and swell do have the characteristics of the surface waves.

In table 8 are listed certain ships which have been frequently mentioned in this paper.

TABLE 8.—*List of ships quoted in the present paper (from Kaigun-Yôran, 1935)*

Name	Type of ships	Tonnage (displacement)
Amagiri	Destroyer (1)	1,700
Asakaze	do	1,270
Ashigara	Cruiser (1)	10,000
Haguro	do	10,000
Hanekaze	Destroyer (1)	1,215
Hatsuyuki	do	1,700
Hôshô	Aircraft carrier	7,470
Itsukushima	Mine-layer	1,970
Kamui	Seaplane carrier	17,000
Kinu	Cruiser (2)	5,170
Kiso	do (2)	5,100
Kitakami	do (2)	5,100
Mikuma	do (2)	8,500
Mogami	do (2)	8,500
Myôkô	do (1)	10,000
Nachi	do (1)	10,000
Naka	do (2)	5,195
Ooi	do (2)	5,100
Ryûzyô	Aircraft carrier	7,100
Sendai	Cruiser (2)	5,195
Susaki	Transport ship	8,800
Taigei	Submarine depot-ship	10,000
Tenryû	Cruiser (2)	3,230
Tsurumi	Transport ship	14,050
Yûgiri	Destroyer (1)	1,700
Destroyer:		
Extra class		1,700
Tsuki class		1,315
Kaze class		1,270

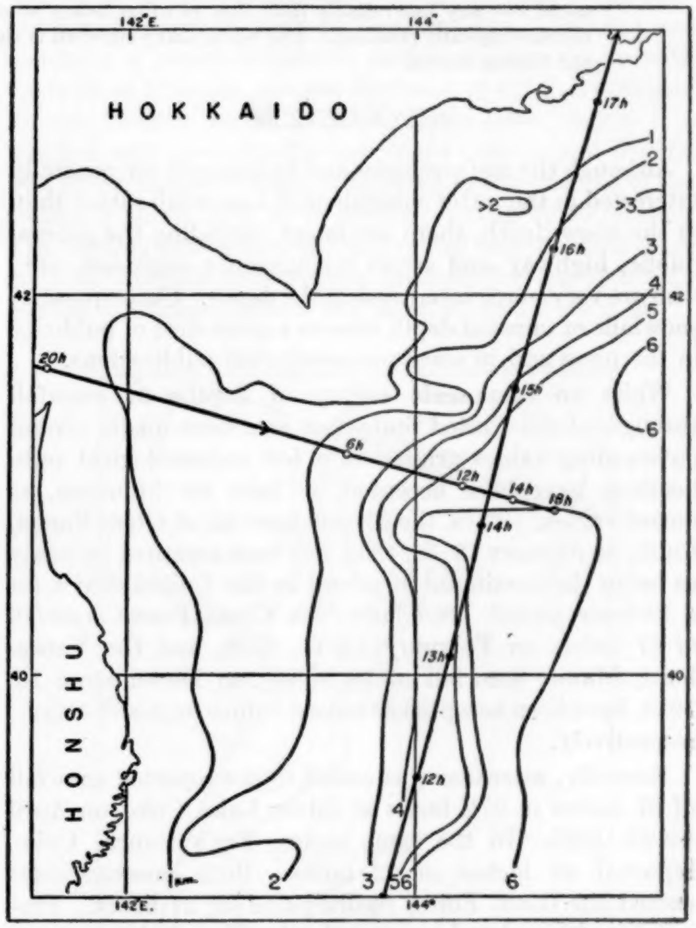

FIGURE 6.—Path of the typhoon center during the critical period from 1100 to 1700 JMT September 26, 1935. Dots indicate hourly positions (JMT) of the center, and circles the positions of the main naval squadron from 2000 JMT, September 25 to 1800 JMT, September 26. Isolines of constant sea depth are drawn for each 1000 meters.

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RECORD SNOWFALL OF APRIL 14-15, 1921, AT SILVER LAKE, COLORADO

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ABSTRACT

A snowfall of 87 inches in 27½ hours on April 14-15, 1921, was reported at Silver Lake, Colo. This snowfall, if correctly measured, exceeds others generally accepted as being record values for the United States. Consequently it is important to determine the reliability of the observation. There is no evidence to indicate that the measurement was any less reliable than that of other heavy snowfalls, and it appears that a snowfall of this magnitude is meteorologically possible. The Silver Lake snowfall is therefore acceptable as the highest known recorded value for the United States.

INTRODUCTION

Although the meteorologist and hydrologist are generally interested in the water equivalent of a snowfall rather than in the snow depth, there are many, including the general public, highway and street maintenance engineers, etc., who are very much interested in the depth. Consequently, snowfalls of unusual depth receive a great deal of publicity in the press and in some meteorological publications.

While no large-scale survey of depths of snowfall throughout the United States has ever been made, several outstanding values printed in a few meteorological publications have been accepted, at least by inference, as record values. Thus, the 60-inch snowfall at Giant Forest, Calif., on January 18-19, 1933, has been accepted by many as being the maximum of record in the United States for a 24-hour period. Similarly, the Giant Forest snowfall of 87 inches on February 12-14, 1926, and the Vanceboro, Maine, snowfall of 96 inches on December 6-10, 1933, have been accepted as record values for 3 and 4 days, respectively.

Recently, attention was called to the reported snowfall of 87 inches in 27½ hours at Silver Lake, Colo., on April 14-15, 1921. In the same storm, Fry's Ranch, Colo., reported 62 inches in 22 hours. Both measurements exceed the Giant Forest record value for 24 hours. Prorated for 22- and 24-hour periods, the Silver Lake measurement yields 70 and 76 inches, respectively, indicating without doubt an outstanding snowfall rate for those durations. The 87-inch measurement actually equaled the amount generally accepted as being the record value for three days that was observed at Giant Forest on February 12-14, 1926.

The Silver Lake snowfall continued beyond the 27½-hour period to establish new records. During the 32½-hour period of more or less continuous snowfall from 1430 MST, April 14 to 2300 MST, April 15, 95 inches was reported. If the small snowfalls of April 12 and 13 are added to this amount, a record value of 100 inches in a total elapsed time (including breaks) of 85 hours is obtained. This value exceeds the generally accepted previous record of 96 inches in four days at Vanceboro, Maine, on December 6-10, 1933. The records established by the Silver Lake snowfall are as follows:

Duration (hours)	*Depth (inches)*	*Date*
24	[1] 76	Apr. 14-15, 1921
27½	87	Do.
[2] 32½	95	Do.
48	95	Apr. 13-15, 1921
72	98	Apr. 12-15, 1921
85	100	Do.

[1] Prorated.

[2] Longest period of apparently continuous snow.

EVALUATION OF RELIABILITY

Because of the new records established, the Silver Lake measurement was examined very thoroughly before being accepted. High winds on April 15 undoubtedly drifted the snow and made it difficult to choose a site having a representative depth. However, there is no evidence to indicate that the Silver Lake observer used less care in obtaining a representative snow depth than did the observers who measured the previous record snowfalls at Giant Forest and Vanceboro, which were also evidently accompanied by relatively high winds. Consequently, the Silver Lake measurement cannot be discarded on this basis.

The water equivalent of the major portion of the snowfall, the 87 inches which fell in the 27½ hours between 1430 MST, April 14, and 1800 MST, April 15, was reported as 5.60 inches, making the snow density (ratio of water equivalent to snow depth) 0.06. This low value of snow density is not unusual at the 10,000-ft. level (Silver Lake elevation 10,220 ft.), but does appear low for a snow layer more than 7 feet deep. However, of 16 stations above the 7,000-ft. level in the area reporting snowfall in the same storm, eleven reported snow densities under 0.10 and none over 0.13. Table 1, which lists the stations in decreasing order of elevation, shows that the water equivalent at Silver Lake compares favorably with that at other stations in the vicinity.

TABLE 1.—*Snow density at stations above the 7,000-ft. level in Apr. 14–15, 1921, Colorado storm*

Station	Elevation (ft.)	Snow depth (in.)	Water equiv. (in.)	Snow density
Lake Moraine	10, 265	33	2. 33	0. 07
Silver Lake	10, 220	95	6. 40	. 07
Victor	10, 100	15	1. 23	. 08
La Veta Pass	9, 242	48	1. 87	. 04
Longs Peak	9, 000	50	4. 93	. 10
Hartsell	8, 900	17	1. 34	. 08
Fremont Experiment Station	8, 850	49	6. 28	. 13
Dillon	8, 800	24	1. 92	. 08
Fraser	8, 560	49	3. 18	. 06
Georgetown	8, 550	52	3. 77	. 07
Elk Creek	8, 440	37	2. 52	. 07
Grand Lake	8, 380	48	3. 00	. 06
Estes Park	8, 000	48	3. 86	. 08
Idaho Springs	7, 543	48	4. 90	. 10
Fry's Ranch	7, 500	62	7. 65	. 12
Monument	7, 200	37	4. 05	. 11

Also, the Silver Lake storm precipitation is consistent with that of the stations in the region as shown by the total-storm isohyetal map of figure 1 for the 36-hour period from 1100 MST, April 14 to 2300 MST, April 15, which embraces practically all the heavy precipitation for the entire storm.

For further confirmation of the Silver Lake precipitation, the amounts shown on the map of figure 1 were expressed in terms of percentage of the mean annual precipitation at the respective stations and plotted on the map of figure 2. This map indicates that the water equivalent at Silver Lake could be higher and still agree with that of other stations.

There is little doubt as to the meteorological possibility of the prorated water equivalent of 4.90 inches in 24 hours. Denver, about 40 miles southeast of Silver Lake, reported the following air and dewpoint temperatures and winds on April 14 and 15:

	6 AM	*Noon*	*6 PM*
Apr. 14	41°–34°	52°–34°	44°–40°
	W2	N9	E15
Apr. 15	36°–35°	30°–29°	28°–26°
	NE20	N33	NW24

Taking 32° F. as a conservative estimate of the mean dewpoint from noon to noon at Denver (elev. 5,283 ft.) and assuming a pseudo-adiabatic saturated atmosphere with sea level at 1000 mb., a mean dewpoint of 15° F. is obtained for the 24-hour period at Silver Lake (elev. 10,220 ft.), which is only about 3 miles east of the Continental Divide. The mean east-west slope of the area in the vicinity of the station is about 2,500 ft. in 5 miles, or roughly 10 percent. The vertical component of a horizontal onslope wind of 30 m. p. h., another conservative estimate for the 10,000-ft. level in a storm situation, is 3 m. p. h., or 1.3 m. p. s.

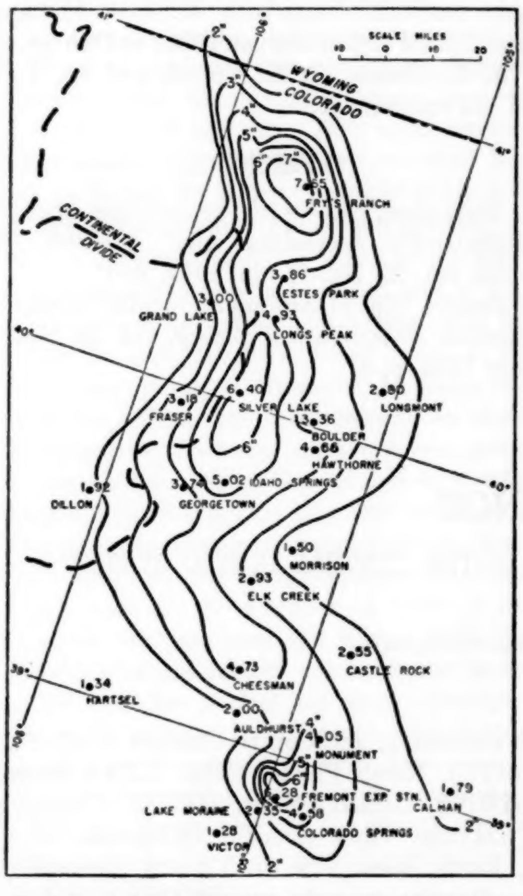

FIGURE 1.—Total-storm isohyetal map for 36 hours from 1100 MST, April 14 to 2300 MST, April 15, 1921.

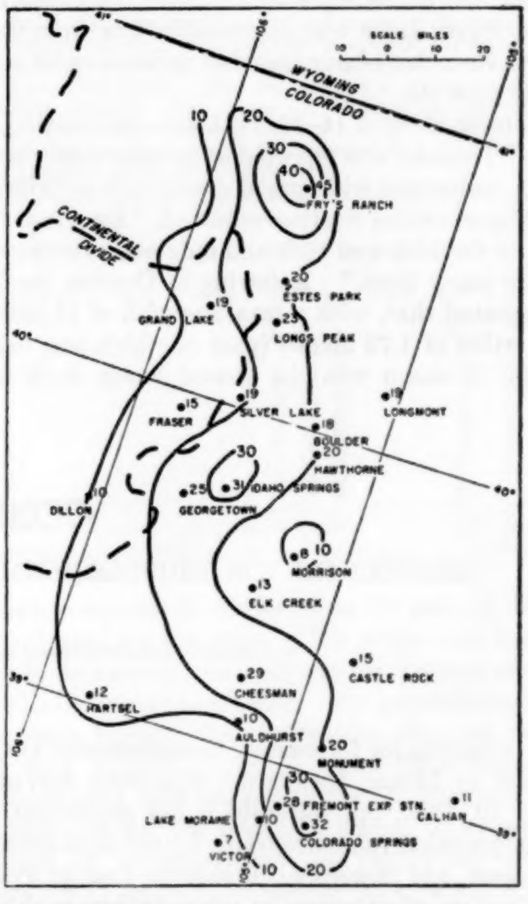

FIGURE 2.—Isopleths of total-storm precipitation of figure 1 expressed in percentage of mean annual precipitation.

Showalter's formula [1] for computing precipitation rates from a column of pseudo-adiabatically ascending air is

$$I=\frac{V_{s_0}\rho_0(x_0-x_1)}{7} \tag{1}$$

where I is the precipitation rate (in./hr.), V_s is the vertical speed (m./s.), ρ_0 is the air density (kg./m.^{3}), and x is the mixing ratio (g./kg.), the subscripts 0 and 1 referring to the base and top of the air column, respectively. For a column with base at 10,220 ft. and top at 20,000 ft. and the preceding assumed conditions of wind, temperature, and humidity, equation (1) yields

$$I=\frac{1.3\times 0.898(2.54-0.38)}{7}=0.36 \text{ in./hr.} \tag{2}$$

or 8.64 inches in 24 hours, which is about 176 percent of the amount estimated to have fallen. These computations indicate the 24-hour 76-inch snowfall is theoretically possible under the assumed conditions even if the snow density were as high as 0.11.

Also, it should be noted that Brooks [2] once roughly estimated that the maximum possible 24-hour fall of snow with density of 0.10 under normal packing conditions would be approximately 6 feet. Since the density of the snow at Silver Lake was appreciably less than 0.10, the prorated 76-inch 24-hour snowfall appears to be meteorologically possible.

The storm of April 14–16, 1921 was outstanding for the region. Thunder was reported at several widely scattered stations, indicating widespread convective activity. Fremont Experimental Station reported, "Heaviest snow of record on the 14th and 15th and only one ever recorded as breaking many trees." Referring to Denver, the Denver Post reported that, with a total snowfall of 11 inches and precipitation of 1.73 inches (part of which was rain), the April 14–15 storm was the second worst April blizzard since 1885. Snow drifted to a depth of 7 feet in many parts of the city. The Moffat road was tied up with drifting snow 8 feet deep just west of Corona. The storm was the worst in 5 years at Colorado Springs, where 19 inches of snow were reported. Splintered telephone and telegraph poles were strewn all the way from Denver to Colorado Springs.

CONCLUSION

The above considerations lead to the conclusion that the Silver Lake measurement is reasonable. There is no evidence to indicate that it was less accurate than the measurement of the snowfalls that until now have been accepted as record values, which, incidentally, have been exceeded several times if estimates by Weather Bureau personnel experienced in mountain snowfall are accepted as reliable. For these reasons, the Silver Lake snowfall is being accepted as providing the highest known rates in the United States for durations to 4 days.

ACKNOWLEDGMENTS

The assistance of L. H. Seamon, H. A. Scott, and V. S. Murino in collecting and analyzing portions of the data and preparing the maps is gratefully acknowledged. Credit for calling the attention of Central Office to the Silver Lake snowfall belongs to A. W. Cook, Meteorologist in Charge of the Weather Bureau Office at Denver. M. A. Kohler, A. L. Shands, C. K. Vestal, and W. T. Wilson reviewed the manuscript.

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CORRESPONDENCE

REMARKS ON "ON THUNDERSTORM FORECASTING IN THE CENTRAL UNITED STATES"

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April 10, 1953

The technique for forecasting thunderstorms at Chicago described by Means (MONTHLY WEATHER REVIEW, vol. 80, No. 10, 1952, pp. 165–189) is not dependent upon a rigid geographical reference frame for the data determining the forecast, and therefore it is in order that an evaluation be made of its effectiveness at other stations in the central United States. For this purpose, forecasts for each day of June, July, and August, 1952 were made for the following nine stations in addition to Chicago itself: St. Cloud, Minn. (STC), North Platte, Nebr. (LBF), Dodge City, Kans. (DDC), Omaha, Nebr. (OMA), Columbia, Mo. (CBI), Dayton, Ohio (DAY), Oklahoma City, Okla. (OKC), Little Rock, Ark. (LIT), and Nashville, Tenn. (BNA). Results strongly suggest that local forecasters, particularly in the North Central States, may benefit from studying the article and putting the technique into

routine use at their stations as an aid in forecasting thunderstorms during the coming summer months.

Through the use of Means' technique, 920 forecasts were made, one for each of the ten stations for each of the 92 days. These were verified by using original airways reports from the individual stations, and the requirement for verification is the same as that used by Means—thunder heard at the station between 1230 CST of the forecast day and 1230 CST of the following day.

Experience in applying the three stratifications required to make a forecast gives rise to the following remarks. The first stratification, which consists of classifying the case into 1 of 11 types or subtypes depending basically on the temperature advection pattern at 850 mb., requires clarification in borderline cases. In such cases, it is best to select the type which is moving toward the station. When this cannot be done, and one of the possible types is favorable for thunderstorm occurrence, then that type should be selected so that the final forecast may be determined by further stratification.

The second stratification need be applied only to cases which have first fallen into a type favorable for thunderstorm occurrence. It consists of the examination of surface maps for the occurrence of thunderstorms within certain areas in the twelve hours preceding the time of the forecast. In the most frequently occurring of the types favorable for thunderstorms, the pre-trough warm advection type, the area used is a triangle whose altitude must be oriented along the bisector of an angle between contours and isotherms at 850 mb. It is often found necessary when gradients are weak to draw contours for every 20 feet and isotherms for every degree in order to get an angle of intersection reasonably near the station.

When thunderstorm activity is found in the prescribed area, the final stratification is required and is made by reference to a critical line on a chart of lapse rate between the 850- and 500-mb. levels vs. dew point at 850 mb. (fig. 37 of Means' paper). However, it seems that the usefulness of the critical line must depend on the actual 850-mb. temperature if we are to have a real measure of convective instability. Thus the critical line, which on this stability-moisture diagram has been selected as the locus of 40 percent incidence of thunderstorms, would not be expected to indicate the same frequency in abnormally warm seasons such as the summer of 1952 or in areas where the mean temperatures are higher than those at Chicago. Both of these factors were present in this test with the result that the critical line on the average represented a mere 25 percent incidence of thunderstorms, a level not usually acceptable to the forecaster. This difficulty was anticipated by Means who in correspondence suggested that we check whether the Showalter stability index might prove to be a successful substitute for the stability-moisture diagram.

First, a test was made to find whether both second and third stratifications are essential to the system. For the 397 cases which go beyond the first stratification by falling into one of the four favorable types, a skill score of 0.18 is attained by the use of both second and third stratifications. If either of the latter is eliminated and the final forecast made by the remaining one, the skill score falls to 0.10. When the final forecast for the 304 cases reaching the third stratification is made, not with Means' stability-moisture chart but instead by requiring a Showalter stability index of zero or less, computed at the same geographical location from which data are taken for the stability-moisture chart, a skill score of 0.23 is attained. This indicates that the stability index may profitably be substituted for the stability-moisture chart in cases reaching the third stratification.

The accompanying figure 1 shows the stability-moisture chart for Chicago with the stability index plotted for each case. At least for this abnormally warm summer season, the stability index permits a no-thunderstorm forecast to be made at Chicago for a group of cases lying on the high side of the critical line and having only an 18 percent incidence of thunderstorms. As shown in table 1 the use of the index tends to increase the percentage of correct forecasts.

TABLE 1.—*Results of applying Means' technique to ten stations in the central United States. Columns give the number of cases according to the code: A, thunderstorm forecast and observed; B, thunderstorm observed but not forecast; C, thunderstorm forecast but not observed; D, no thunderstorm forecast or observed. The percent correct is calculated from $(A+D)/92$. The last column is the percent correct from similar columnar data, A and D, for forecasts determined by substituting a Showalter stability index of zero or less for the 40 percent discriminating line of the stability-moisture diagram in the third stratification of the Means technique*

	Original Means technique					With Showalter S. I. substituted
	A	B	C	D	Percent correct	Percent correct
Chicago	14	3	24	51	71	82
St. Cloud	17	11	14	50	73	73
North Platte	18	13	11	50	74	72
Dodge City	13	9	18	52	71	71
Omaha	16	19	26	31	51	60
Columbia	16	11	14	51	73	74
Dayton	10	10	10	62	78	78
Oklahoma City	6	8	20	58	70	73
Little Rock	2	17	10	63	71	76
Nashville	7	12	15	58	71	74
Total	119	113	162	526	70	73

The relative success of the forecasts for each of the stations is indicated by the data in the table. An attempt was made to find one or more reasons for the poor showing made by the technique at Omaha. No general conclusion could be made beyond the observation that the failures occurred with rapidly changing types thus suggesting that the forecaster lean toward use of an incoming type. A few additional failures could be traced to subsequent development of thunderstorms in pre-frontal troughs which were dry at the time the prescribed area was checked for past thunderstorms.

The period covered by this test was not a long one but

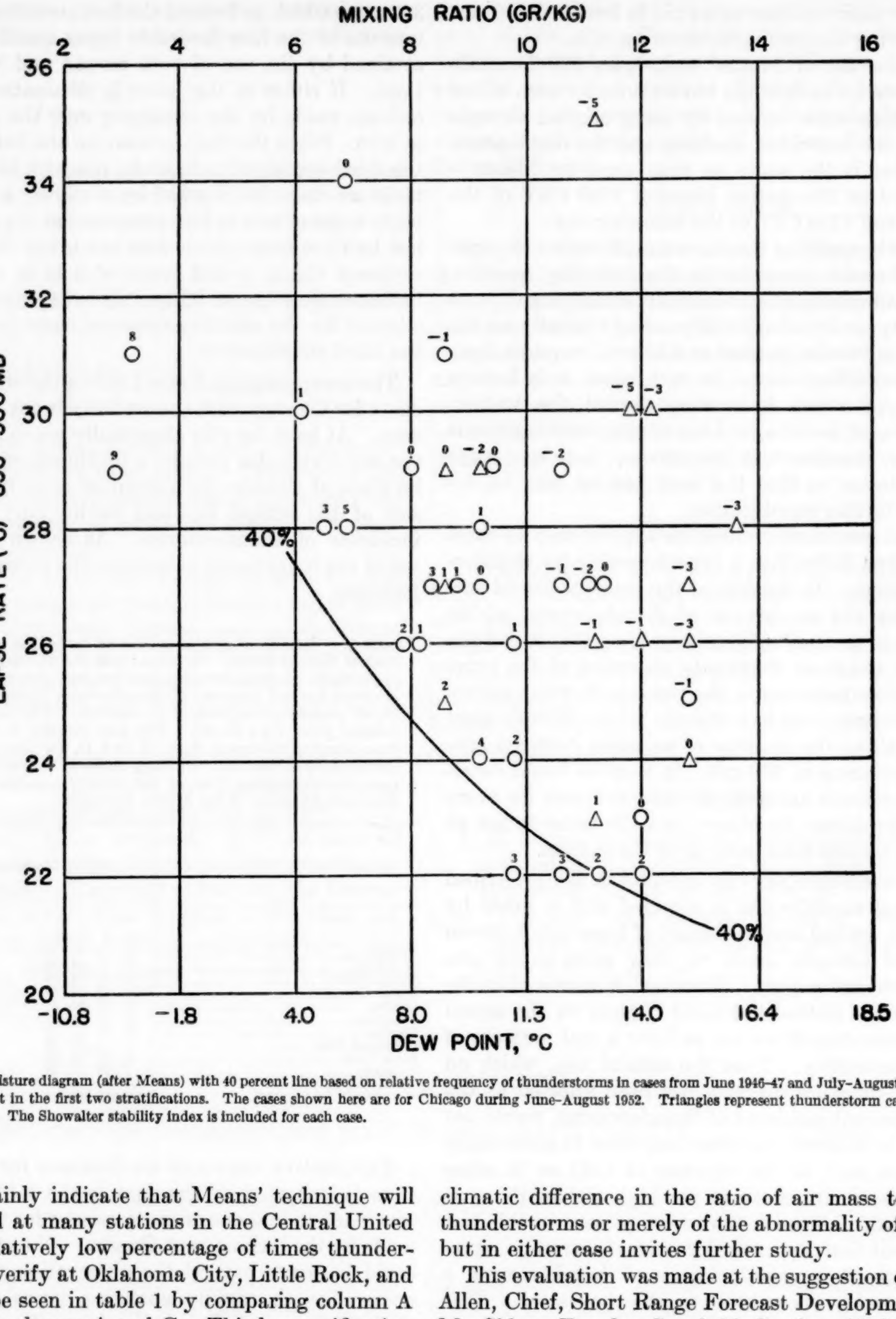

FIGURE 1.—Stability-moisture diagram (after Means) with 40 percent line based on relative frequency of thunderstorms in cases from June 1946–47 and July–August 1945–46–47 which are not separated out in the first two stratifications. The cases shown here are for Chicago during June–August 1952. Triangles represent thunderstorm cases, circles are no-thunderstorm cases. The Showalter stability index is included for each case.

the results certainly indicate that Means' technique will be found helpful at many stations in the Central United States. The relatively low percentage of times thunderstorm forecasts verify at Oklahoma City, Little Rock, and Nashville may be seen in table 1 by comparing column A with the sum of columns A and C. This low verification at the three southernmost stations may be a result of a climatic difference in the ratio of air mass to prefrontal thunderstorms or merely of the abnormality of the season, but in either case invites further study.

This evaluation was made at the suggestion of Mr. R. A. Allen, Chief, Short Range Forecast Development Section. Mr. Sidney Teweles, Jr. of this Section aided in reporting the results.

THE WEATHER AND CIRCULATION OF FEBRUARY 1953[1]

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THE CIRCULATION

The monthly mean 700-mb. circulation over the Northern Hemisphere for February 1953 (fig. 1), featured the existence of three planetary troughs in the main band of westerlies at middle latitudes. These were located in the west-central Pacific, eastern Europe, and North America. Although the latter trough consisted of two pieces, it may be considered essentially as a single trough extending from Baffin Island through eastern Canada and the Great Lakes to Lower California. This trough, in combination with the ridges to either side, was responsible for a large part of the weather over the United States

[1] See Charts I–XV following page 52 for analyzed climatological data for the month.

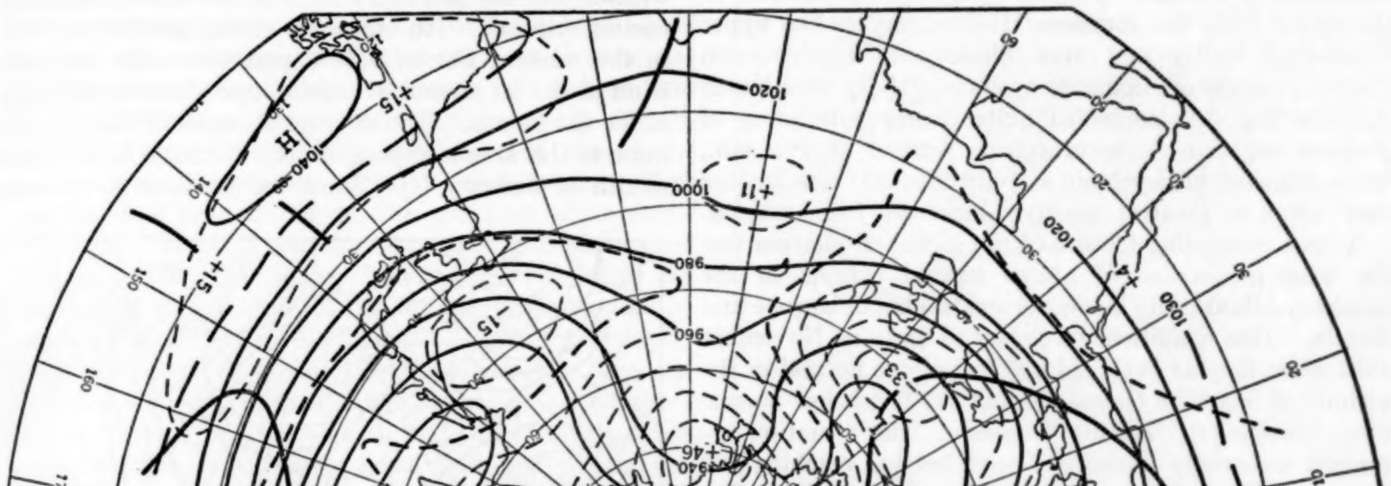

FIGURE 1.—Mean 700-mb. height contours and departures from normal (both labeled in tens of feet) for January 27–February 25, 1953. Of special interest is the strong gradient in eastern Pacific resulting from the well-developed Aleutian Low and Pacific High.

during the month. Other features of the broad scale circulation which directly influenced this month's weather are the strong Aleutian Low, with 700-mb. heights 380 feet below normal and surface pressures 9 mb. below normal, and the well developed Pacific High off the west coast of the United States, with 700-mb. heights 400 feet above normal and sea level pressures 10 mb. greater than normal (Chart XI, Inset). The combination of these two features was associated with a strong belt of west-southwesterly winds across the Pacific at middle latitudes at the 700-mb. level (fig. 2). This jet reached a maximum speed of 56 m. p. h. as an average for the month, and was the primary cause for the preponderance of Pacific air masses over the United States.

Over North America, 700-mb. heights were mostly above normal, with greatest positive departures along the west and east coasts of the United States and in extreme northeastern Canada. Negative departures occurred in the region from the southern Hudson Bay to the upper Mississippi Valley and over Alaska and northwestern Canada. Areas of maximum cyclonic activity over North America (fig. 3A) coincided quite closely with areas of greatest negative departures from normal at 700 mb., while principal anticyclonic activity (fig. 3B) was located near areas of greatest positive departure from normal.

A very interesting feature of the global circulation was the long persistence of above normal heights in the northern Atlantic and below normal heights in Europe and Russia. This condition developed as early as November 1952 when heights averaged 420 feet above normal in the vicinity of Southern Greenland and 300 feet below normal over Europe [1]. During December, the situation remained essentially unchanged with heights reaching 490 feet above normal near southern Greenland and 150 feet below normal over Europe [2]. It was during January that the greatest difference in anomalies occurred. Heights averaged 450 feet above normal west of Great Britain and 330 feet below normal over northwestern Russia, a difference of 880 feet. How this contributed to the European flood was discussed in last month's article [3]. February saw a continuation of this anomalous situation, although not to such an extent as during previous months. Heights averaged 280 feet above normal in the northeastern Atlantic and 330 feet below normal over southwestern Russia. The strong blocking ridge in the North Atlantic was accompanied by fairly slow winds, with speeds along the jet axis averaging approximately one-half the corresponding value in the Pacific (fig. 2).

The circulation at the 200-mb. level (fig. 4) reflects the 700-mb. flow pattern quite closely over North America, showing one major trough extending from Baffin Island southward to the Great Lakes area and then southwestward through Lower California. Two pronounced ridges appear, one extending from western Canada south-southwestward to the eastern Pacific and the other in the northeastern Atlantic. An unusually strong gradient occurred in the western Pacific near Japan where the maximum wind in the jet stream averaged approximately 190 m. p. h. for the month. The average strength of the jet maximum in this area is approximately 122 m. p. h. during the month of January [4]. Since the gradient in this area

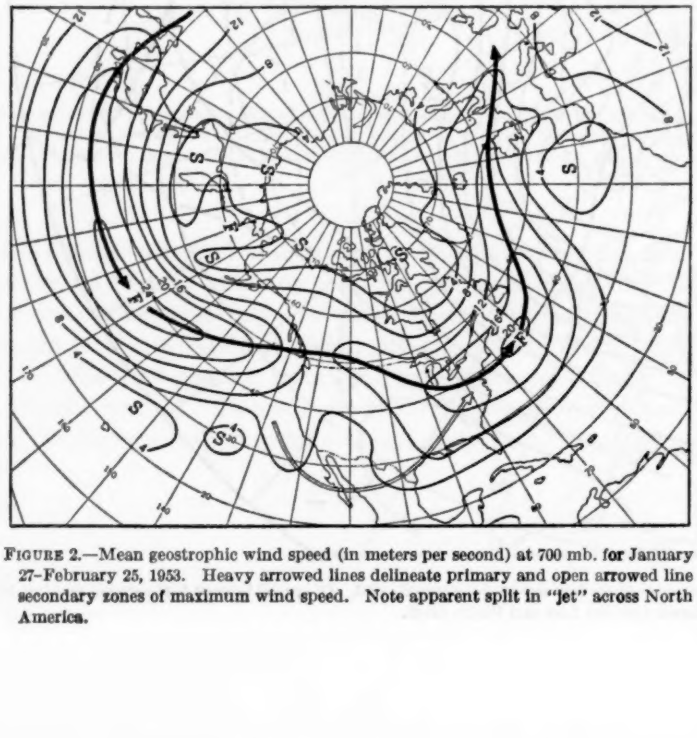

Figure 2.—Mean geostrophic wind speed (in meters per second) at 700 mb. for January 27–February 25, 1953. Heavy arrowed lines delineate primary and open arrowed line secondary zones of maximum wind speed. Note apparent split in "jet" across North America.

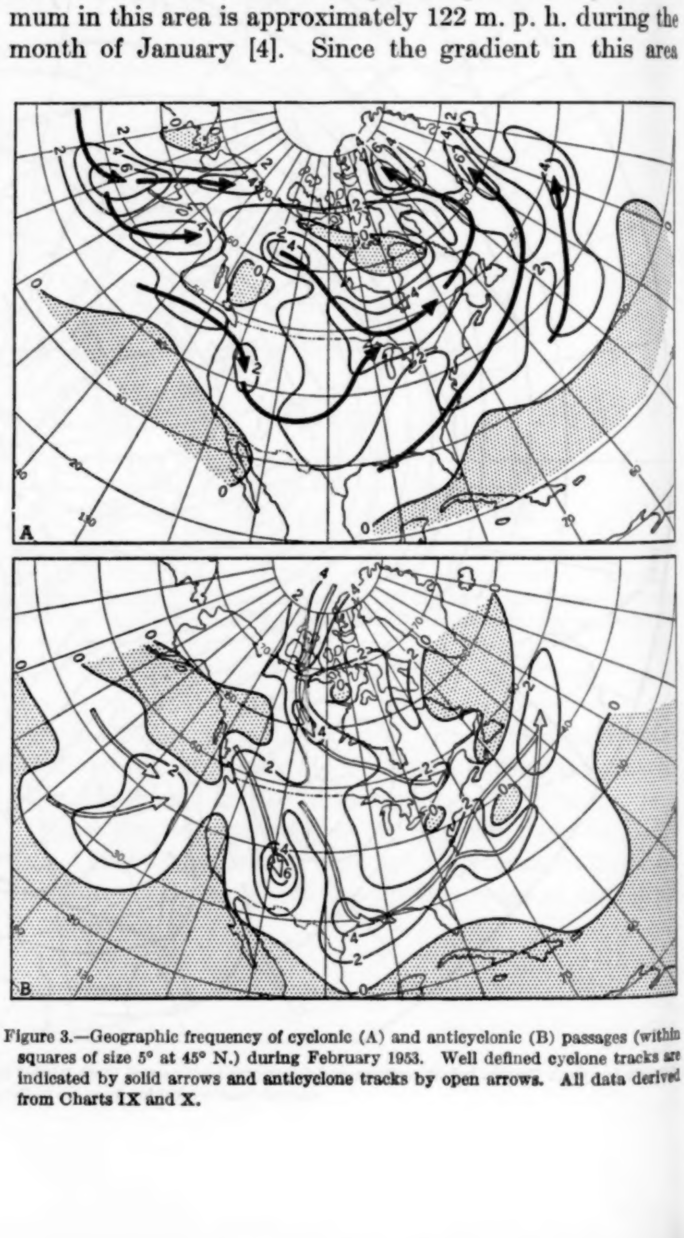

Figure 3.—Geographic frequency of cyclonic (A) and anticyclonic (B) passages (within squares of size 5° at 45° N.) during February 1953. Well defined cyclone tracks are indicated by solid arrows and anticyclone tracks by open arrows. All data derived from Charts IX and X.

varies only slightly from January to February [5], it appears that the speed of the jet was roughly 50 percent greater than normal during February and even stronger than observed in January 1953 [3].

Comparing figures 2 and 4, it is seen that the axes of maximum wind speed at 700 and 200 mb. were fairly similar in location except over the western part of North America, where the jet stream was split at 700 mb. The jet at 200 mb. in the southwestern United States corresponded to the weaker wind stream at 700 mb., while the stronger 700-mb. branch, located over southwestern Canada, had no counterpart at 200 mb. Some light can be thrown on this difference by considering the actual tracks of Highs and Lows (fig. 3) and the relative vorticity field at 700 mb. (fig. 5). Greatest cyclonic vorticity over North America was located in the vicinity of James Bay, with branches extending northwestward into western Canada, northeastward through Quebec and Labrador, and southwestward through the United States to the Gulf of California. Alaska and extreme northern Canada also were dominated by cyclonic vorticity. Elsewhere over North America anticyclonic vorticity prevailed. Principal storm tracks (fig. 3A) paralleled quite closely the axes of greatest cyclonic vorticity, while surface High activity was pronounced in the areas of anticyclonic vorticity. Thus it is seen that the storm path and area of cyclonic vorticity in western Canada corresponded to and was located to the north of the 700-mb. jet across southwestern Canada, while the storm path from the southwestern United States to southern Hudson Bay was located to the north of the 200-mb. jet across the southern United States. This may imply that the northerly storm path consisted principally of Lows shallow in comparison with those in the southerly storm path.

TEMPERATURE AND PRECIPITATION

Temperatures averaged above normal over most of the country during February (Chart I). Negative departures from normal were generally small and confined mostly to the southern border States, sections of the Pacific Coast, and central Rocky Mountain States. The concentration of positive temperature anomalies in northern and negative anomalies in southern sections resulted from a preponderance of polar Pacific air masses over the United States during the month. The same air mass originating in the Pacific may result in above normal temperatures in northern and below normal in southern sections of the country since normal temperatures are considerably higher in the southern as contrasted with the northern border States. Figure 3B shows that most of the anticyclones entering the United States originated in the Pacific, while polar continental Highs were deflected southeastward into eastern Canada seldom entering the United States. Greatest positive temperature anomalies (+8° F. or more) were observed along the northern border States. Foehn activity resulting from the strong belt of westerlies emanating in the Pacific (fig. 2) was responsible for the warmth in the Northern Plains east of the Rockies, while less than normal northerly components of flow (fig. 1) prevented polar continental air from entering the Northeast in normal amounts. Greatest negative temperature departures observed during the month (approximately 2° below normal) occurred in portions of the Gulf Coast States and in the San Joaquin Valley of California.

Precipitation in the United States during the month was greater than normal in more than half the country (Chart III). This could be expected with a major trough aloft located over the central United States and a corresponding area of below normal pressures at the surface (Chart XI, Inset). Actually, two distinct bands of above normal precipitation occurred in line with a split in the path of the principal cyclone track (fig. 3A). One band extended from eastern Texas northeastward through the Middle

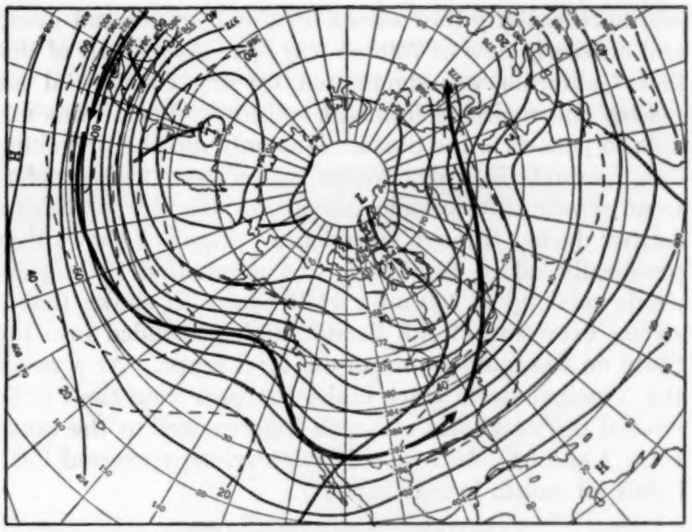

FIGURE 4.—Mean 200-mb. contours (labeled in hundreds of feet) and isotachs (at intervals of 20 m. p. s.) for January 27–February 25, 1953. Solid arrow indicates average "jet" which reached a value of near 190 m. p. h. east of Japan.

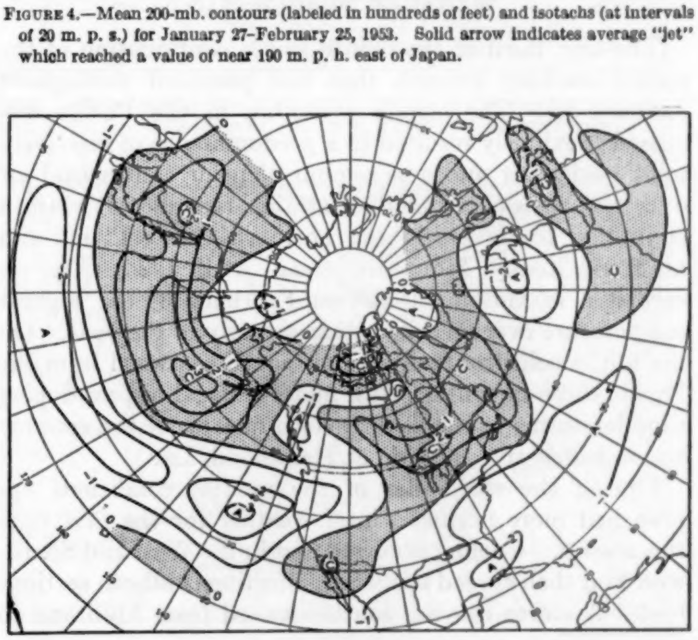

FIGURE 5.—Mean relative geostrophic vorticity at 700 mb. (in units of 10^{-5} sec^{-1}) for January 27–February 25, 1953. Areas of cyclonic vorticity are shaded and labeled "C" at centers of maximum vorticity. Areas of maximum anticyclonic vorticity are labeled "A".

Atlantic States,[2] while the other ran from the Pacific Northwest through the Plains into the Great Lakes region. Less than normal precipitation was general in an area extending from west Texas to New England, which was located between the two major storm paths through the United States. Precipitation was also generally subnormal throughout the southwestern United States. This deficiency was especially marked in California, where an intense and widespread drought affected the State from January 21 to the end of February. In most of California less than 25 percent of normal precipitation fell during the month of February, and in some sections no measurable amounts were recorded (Chart III). For the State as a whole total precipitation during the month averaged only 13 percent of normal. This dry region was produced by a combination of several factors. Most notable perhaps was the prevalence of stronger than normal northeasterly flow at sea level (Chart XI and inset) and northerly flow at 700 mb. (fig. 1). As a result of this flow California was dominated by dry continental air masses and moisture from the southwest Pacific was unable to penetrate the State. Not only did the prevailing flow originate in a dry source region, but it also underwent strong anticyclonic curvature, thereby producing further drying through subsidence. Figure 5 shows that practically all of California was dominated by anticyclonic vorticity at 700 mb., while Chart XI shows that a strong extension of the Pacific High protruded into the State on the monthly mean sea level maps. As a result the principal storm track and jet stream from the Pacific crossed the west coast of North America well to the north (figs. 2 and 3). In fact only one cyclone traversed California all month long (Chart X).

WEATHER HIGHLIGHTS

The first third of the month saw a continuation of the record-breaking warmth that had persisted throughout January [4]. The strong westerlies in the Pacific discussed previously resulted in a predominance of relatively mild Pacific air and a minimum of polar continental air over the States. Individual station records for warmth continued to be set in the northern Great Plains and northern Rocky Mountain areas. Salt Lake City recorded a maximum of 65° on February 3, the highest temperature ever recorded there so early in the year. On the 6th, a cold front which had moved eastward from the Pacific came in contact with moist tropical air, producing thunderstorms in the southeastern quarter of the country and a destructive tornado at Hammond, La.

During the remainder of the month, conditions approached more normal winter weather for the first time this season. Cooling occurred first in the West and Southwest and then spread eastward, affecting southern sections first. A storm moving southeastward from Montana to Kansas created gale winds and dust storms on the 15th and 16th, with winds as high as 55 m. p. h. and dust extending to a height of 14,000 feet in western and south-central Kansas, with somewhat similar conditions in eastern Colorado and parts of Oklahoma and Texas. In this area, inadequate moisture during the fall and winter of 1952–53 had left the soil dry and loose. Another storm moved in from the Pacific on the 17th, deepened over Utah on the 18th, becoming a true "Colorado Low" on the 19th. It then moved northeastward through the Plains and Great Lakes regions on the 20th and 21st. High winds associated with this Low caused dust storms that, in many sections of the lower Great Plains, were the worst since the 1930's. Elsewhere, this storm assumed blizzard proportions, leaving heavy snowfall and high drifts throughout sections of the central and northern Great Plains.

As the storm moved eastward, it picked up additional moisture from the Gulf of Mexico source region, and thunderstorms and heavy rain occurred in the Midwest and South. Tornadoes and severe wind squalls in sections of Alabama, Mississippi, and Louisiana caused death, injuries, and destruction. This storm was followed by severely cold weather over much of the western portion of the country, including the coldest weather of the winter in sections of southern Arizona. Below freezing temperatures caused some crop damage in southern California. The closing week of the month was uneventful with no important storminess occurring, however, frost was still causing some damage in the Southwest.

As a result of persistently above normal temperatures in the Great Lakes Region throughout the early winter and during this month, ice on the lakes was considerably thinner and areal coverage much less than usual as the month closed. It was reported that southern waters had remained mostly open throughout the winter, with very few ice fields in northern waters. Conditions were similar to early 1921 and 1942 seasons, when port openings were abnormally early.

[2] For a detailed description of one of these storms, see adjoining article by Jones and Roe.

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THE NORTHERN GULF LOW OF FEBRUARY 14, 1953

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INTRODUCTION

At midnight February 13, a small area of light rain had appeared over Texas from Austin and Junction southward. Within six hours, thunderstorms and rain were spreading eastward into the Gulf States as far as southern Alabama. By nightfall of the 14th, southern Mississippi and Louisiana had experienced flooding and local damage from heavy rains and gusty north winds. Severe turbulence and thunderstorm activity were disrupting air traffic flow from the Florida coast to southern Louisiana.

From the evaluation of weather data and synoptic charts it was apparent that a storm possessing several remarkable characteristics had moved across the northern Gulf of Mexico. It is the purpose of this study to present some of these features and to offer possible explanations for their occurrence.

LOW LEVEL SYNOPTIC FEATURES

In the period from February 11–13 a cold front had moved across the eastern United States and the Gulf of Mexico leaving a vast body of polar air over the area it had traversed. At 1230 GMT on the 13th, the polar front was quasi-stationary and lay across the southern Gulf to the central Mexican coast and northwestward across Mexico into western New Mexico. At this time a small cyclonic circulation was generating on the front near the southern Arizona-New Mexico border in conjunction with a cold Low aloft over southern Arizona. During the next 18 hours, the surface Low traveled southward and its circulation increased as the central pressure dropped to an estimated 1000 mb. By 0630 GMT on the 14th (fig. 1), the Low lay 50 miles north of Torreon, Mexico (station 382) in the Sierra Madre Oriental. The polar front extended eastward crossing the coast 75 miles south of Brownsville, Tex. Meanwhile the polar High center had weakened slightly and shifted from northeastern Texas to southwestern Georgia. At this time a north-south isallobaric discontinuity line appeared 100 miles west of Brownsville suggesting the formation of a new Low on the polar front between Brownsville and Monterrey, Mexico, 170 miles west. By 1230 GMT that day (fig. 2), the new Low had moved across the southernmost tip of Texas to 27° N., 97° W. and had deepened to a central pressure estimated at 1002 mb. Twelve hours later (fig. 4), the Low was centered 70 miles south of Pensacola, Fla., and was moving east-northeastward at approximately 50 knots. Its central pressure had decreased to 1000 mb. or less. New Orleans District Forecasters estimate that the pressure gradient, computed from time-space considerations of the passage of isobars at New Orleans, would indicate a central pressure near 996 mb. Accelerated deepening took place as the Low turned inland across Georgia and moved up the Atlantic coast.

The six-hourly surface analyses in figures 1 through 4 show the passage of the storm across the Gulf and give some idea of the attendant weather distribution. The increase of thunderstorm intensity in extreme western

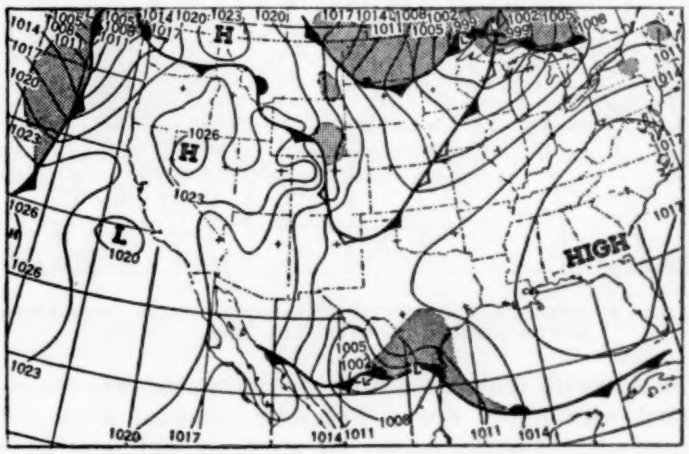

FIGURE 1.—Surface weather chart for 0630 GMT, February 14, 1953, showing the development of the Low along the polar front across Mexico with the precipitation north of it.

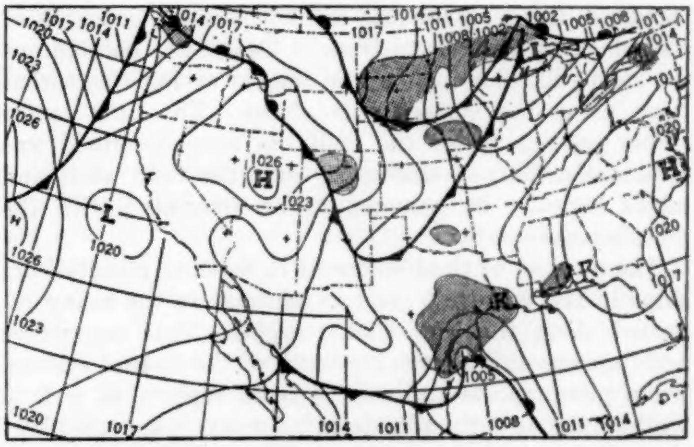

FIGURE 2.—Surface weather chart for 1230 GMT, February 14, 1953. Note the area and movement of the precipitation pattern.

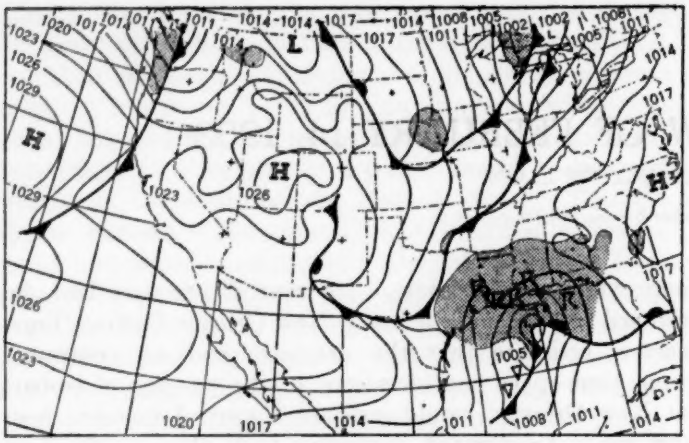

FIGURE 3.—Surface weather chart for 1830 GMT, February 14, 1953. Concentration of the thunderstorm activity is along the coast.

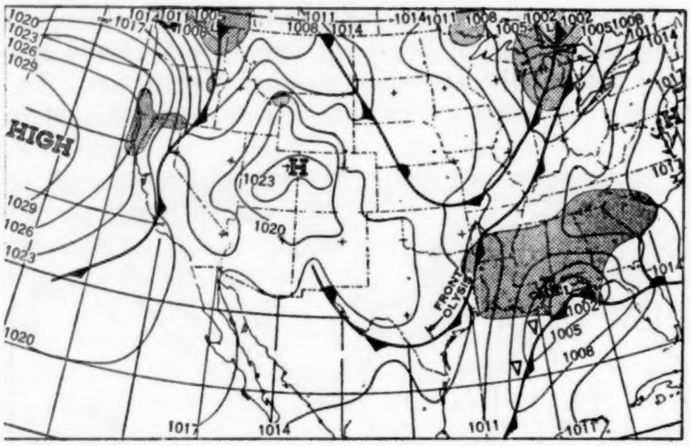

FIGURE 4.—Surface weather chart for 0030 GMT, February 15, 1953. About 3 hours later the surface center moved inland near Panama City, Fla.

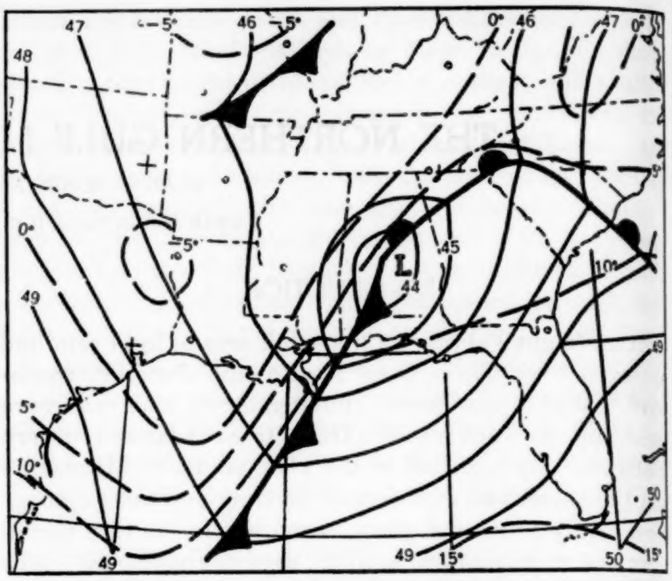

FIGURE 5.—850-mb. chart for 0300 GMT, February 15, 1953, showing the intensity of isotherm packing associated with the cold front.

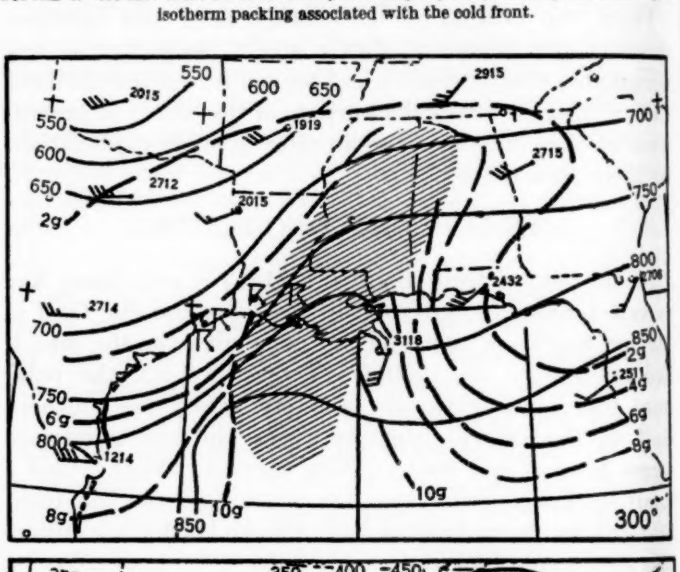

FIGURE 6.—300° A. and 312° A. isentropic surfaces for 1500 GMT, February 14, 1953. Pressure (solid lines) in millibars. Moisture (dashed lines) in grams per kilogram. Hatched area indicates saturation. Numbers indicate the thermal winds (ddff), direction in tens of degrees and force in knots.

Florida with the approach of the storm crest was associated with heavy rains. Pensacola reported a rainfall total of 3.10 inches during the six hours ending at 0030 GMT on the 15th.

The 850-mb. chart of 0300 GMT on the 15th (fig. 5) illustrates the unusual strength of the cold front. Although at this level the cold front joins the warm front in a single crest, the Miami District Center has pointed out the strong likelihood of several smaller cyclonic perturbations along the surface polar front. The Low center whose passage across the Gulf has been described was apparently the one associated with the crest aloft and might logically be assumed to be associated with the most intense weather.

The absence of thunderstorms in weather reports from ships in the mid-Gulf area, in contrast to the many reported along the Gulf Coast, suggests that convective activity was at a maximum north of the frontal system. From pilot reports and coastal radar reports, as well as station reports of thunderstorm intensity, it appears likely that airmass turbulence increased toward the wave crest. The constant pressure charts at low levels indicate the

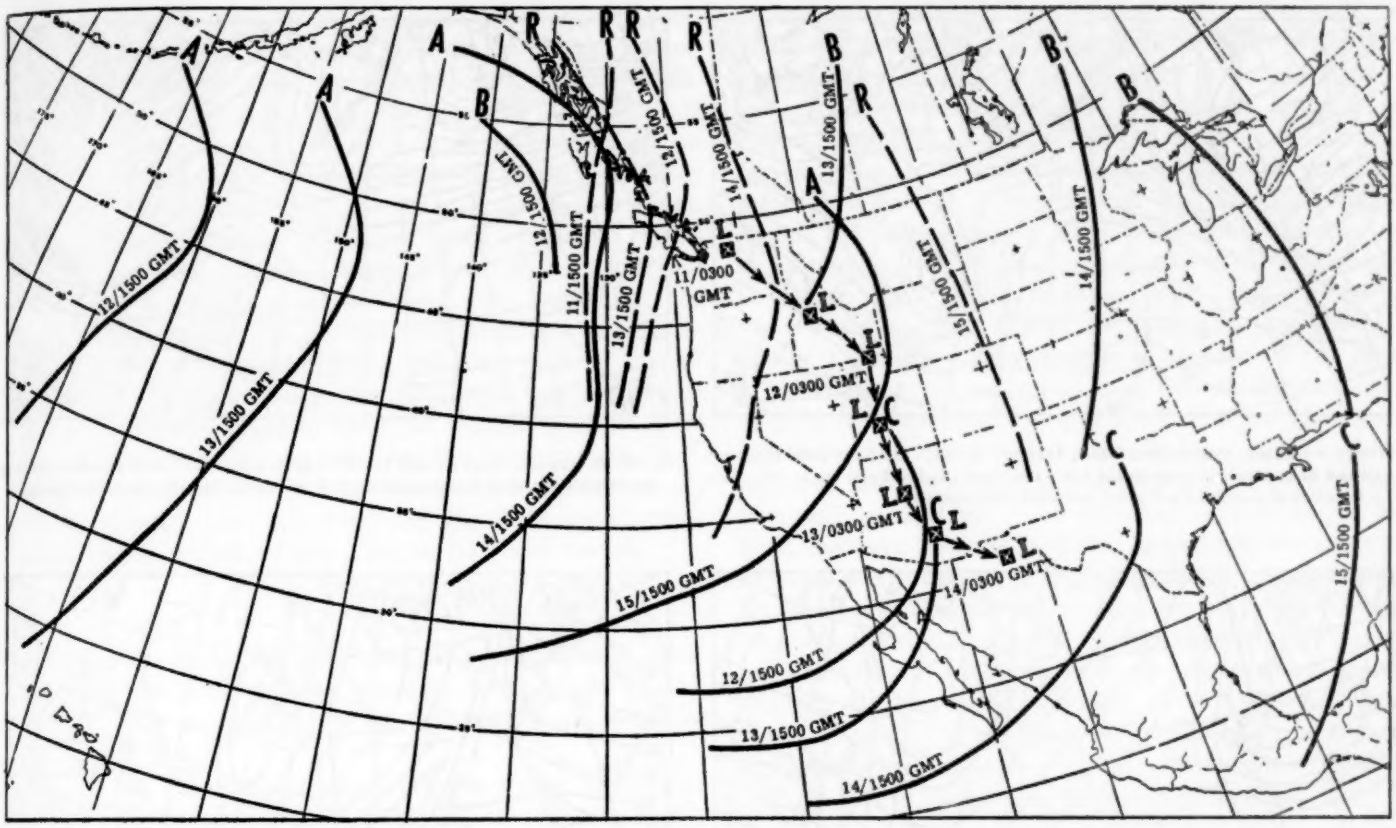

FIGURE 7.—500-mb trough-ridge analysis. Solid lines indicate troughs at 24-hour intervals, dashed lines indicate the ridge (R) at 24-hour intervals, and the arrow indicates the track of the Low (L) at 12-hour intervals. (A) indicates the Pacific trough, (B) the Canadian trough, and (C) the Southwest trough.

pronounced thrust of cold air against the moist air in advance of it. The vertical action is further clarified by the isentropic analyses for 1500 GMT on the 14th shown in figure 6. From an examination of the soundings, the 300° A. and 312° A. potential temperature surfaces were chosen in order to portray the interaction of dry and moist tongues taking place between low and intermediate levels. The drive eastward of the dry tongue at 312° produced sufficient convective instability over southernmost Louisiana to result in a break-through of moisture from the lower levels into this dry air. Soundings 12 hours later revealed pronounced vertical diffusion of moisture with the trend toward stabilization in the moist air as thunderstorms disappeared and steady rainfall developed.

The turbulence of the atmosphere north of the wave was quite evident in the chaotic pressure traces delineated by barograms at stations from southern Louisiana through southern Alabama and westernmost Florida. These barograms have been studied by the members of the Weather Bureau Pressure Jump Project who identified two predominate features of tendency behavior. One consisted of a line of sharp pressure drops whose magnitude was of the order of 0.140 inch in ten minutes, the other a line of pressure jumps of the order of 0.100 inch in ten minutes. The isochrones of pressure drop showed an average speed of 63 m. p. h. northeastward in a direction normal to the isochrones. The pressure jump isochrones averaged 32 m. p. h. east-southeastward, intersecting the drop isochrones along a line from a point just west of New Orleans at 2200 GMT on the 14th to a point 40 miles south of Mobile near 0000 GMT on the 15th and to just south of Marianna, Fla., by 0230 GMT. To the north of the intersection line the jump preceded the drop, to the south the drop preceded the jump. The interpretation given to these pressure variations is that they reflect marked local fluctuation of the frontal surface. Consequently adjacent to the line of intersection the almost simultaneous reversal of pressure change of the magnitude involved would produce extremely chaotic air motions.

500-MB. FEATURES

In the following discussion, frequent reference will be made to the 500-mb. trough-ridge analysis in figure 7. In the first two weeks of February, high level circulation patterns had maintained a regime of relatively large amplitude waves slowly retrograding westward over North America. By the tenth of the month the 500-mb. ridge lay along the west coast between two main troughs. The first of these extended from the Dakotas southwestward; the second trailed southward from a Low at 45° N., 175° W. A cold tongue was moving across the top of the west coast ridge into western Canada, forming a closed Low (L) over northern Washington by 0300 GMT on the 11th

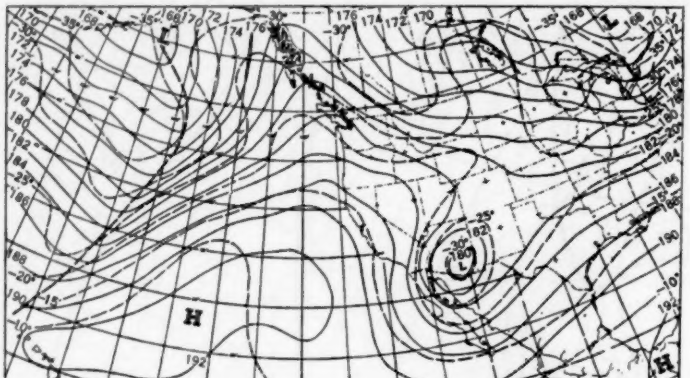

FIGURE 8.—500-mb. chart for 1500 GMT, February 13, 1953. Contours (solid lines) are labeled in hundreds of geopotential feet. Isotherms (dashed lines) are in °C. This is the chart from which the Fjørtoft prognosis was constructed.

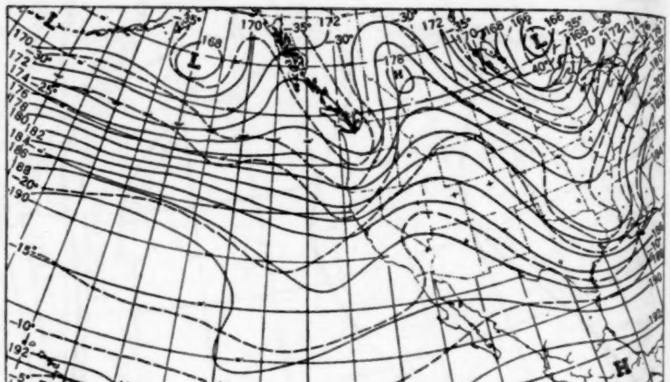

FIGURE 10.—500-mb. chart for 0300 GMT, February 15, 1953. Note the movement of the Southwest trough and the alignment of this trough and the Canadian through.

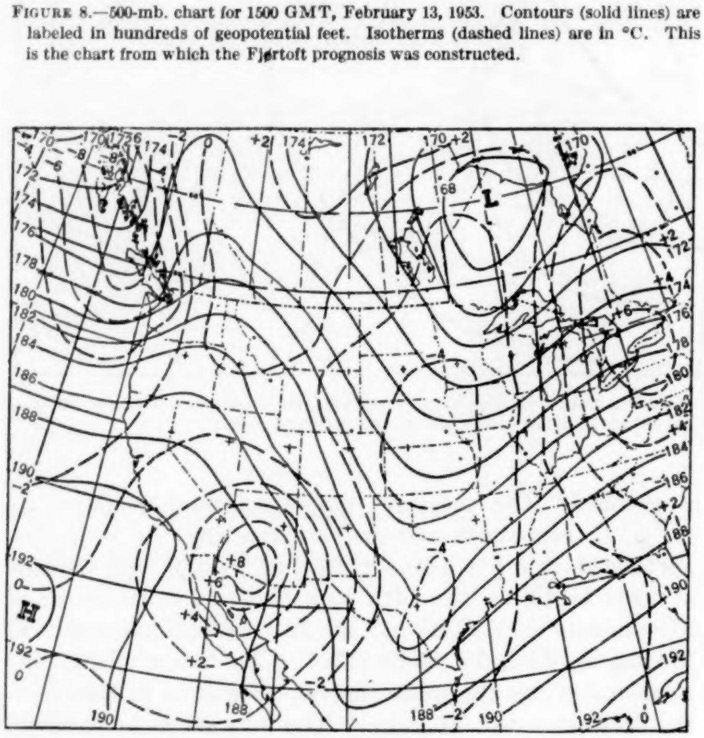

FIGURE 9.—500-mb. chart for 1500 GMT, February 14, 1953. 24-hour height changes (dashed lines) are drawn for 200-foot intervals.

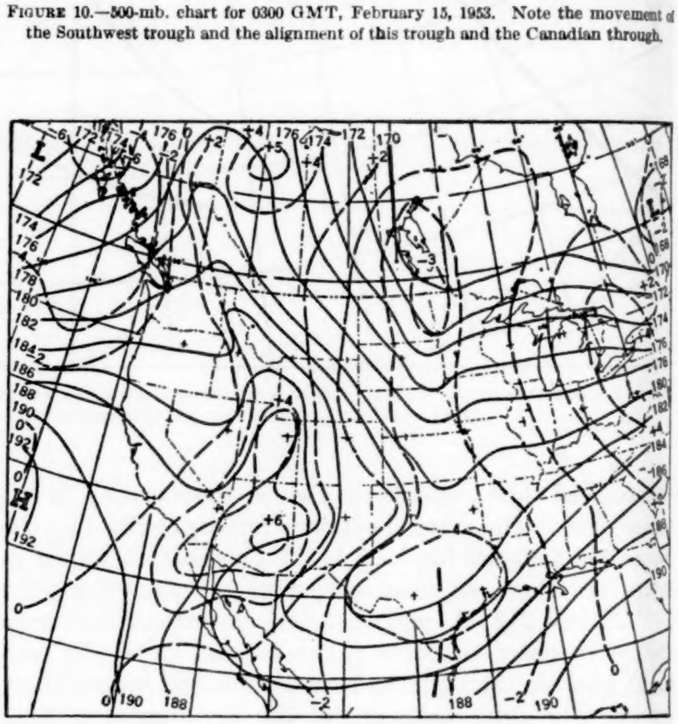

FIGURE 11.—500-mb. 24-hour prognostic chart verifying at 1500 GMT, February 14, 1953, with 24-hour prognosticated height changes (dashed lines) using Fjørtoft integration method. Compare the location of the centers of height changes with the actual 24-hour changes of figure 9.

(fig. 7). The Low (L) then moved southward, reaching southern Arizona by 1500 GMT on the 13th. Meanwhile another cold tongue (B) had made its way from the southern Gulf of Alaska into Alberta and Montana. Pacific trough (A) had accelerated eastward, reaching 155° W. at this time.

By 1500 GMT on the 14th, Pacific trough (A) was entering the west coast, displacing ridge (R) ahead of it, and forcing the Arizona Low (now trough C) eastward to join trough (B) over eastern Texas. The eastward push of cold air in trough (C) produced a steep thermal gradient of 9° C. between Brownsville and San Antonio at 500 mb. In turn the southwest wind belt from southern Texas to Georgia suddenly strengthened to form a jet whose maximum velocity was at least 80 knots. Simultaneously the surface Low beneath it assumed its rapid movement across the Gulf.

Although trough B-C was moving eastward at an average speed of 30 knots, the centers of 12-hour height fall and surface pressure fall were moving to the east at 40–45 knots and maintaining a separation of about 450 miles. This suggests that the strong winds over the path of the Low were related rather directly to the rapid movement of the Low. The movement of trough B-C is not to be ignored, but the possibility is suggested that the impulse associated with its motion traveled eastward with a speed exceeding that of the trough.

The 500-mb. charts (figs. 8 and 10) at 1500 GMT on the 13th and 0300 GMT on the 15th portray conditions pre-

ceding and following the Gulf storm. As has been summarized above, the integration of several important actions took place in producing the marked difference in circulation patterns shown by these charts. The 500-mb. chart for 1500 GMT on the 14th (fig. 9) shows the pattern at the time when complete integration took place, coinciding with the development and movement of the surface storm. It is probable that the low level action would have been weaker or even absent if these several actions had not combined simultaneously as shown. In particular, the cold tongue at 500 mb. moved from Montana southeastward in time to reinforce the cold air moving out of Arizona. This junction in the east Texas region was at a critical time and place to have the maximum effect upon the surface Low starting out over the northwestern Gulf. This in turn could not have occurred if the oncoming Pacific trough had not displaced the west coast ridge, with resultant shift of the Arizona Low and trough.

500-MB. PROGNOSIS

From the preceding summary it is clear that a prognostic 500-mb. chart constructed to verify at 1500 GMT on the 14th should include the following features to be accurate:

1. The Pacific trough and zonal flow over the Pacific region.
2. The major trough in the middle of the country, composed of the developing trough from Montana and the cold trough from Arizona.
3. The eastward movement of height falls imbedded in a strong southwest wind current over the northern Gulf.

In the preparation of such a prognostic chart by subjective methods the following facts up to and including the charts of 1500 GMT on the 13th were noted:

1. The Pacific trough was moving eastward, the 500-mb. level at ship station "Q" west of the trough showing persistent warming with strengthening west wind.
2. Isotherms in the cold air over western Canada were moving southeastward at a regular rate, with the speed of the wind normal to them.
3. The axis of the 12-hour height tendency field around the Arizona Low was rotating from north-south to northwest-southeast by 1500 GMT on the 13th.
4. The thermal and contour gradients in the soutly east quadrant of the Arizona Low were slowh-tightening.

From the above considerations the general trend of events might have been determined subjectively 24 hours in advance. The specific trend was more difficult to assess, unless an objective approach could be found. In an attempt to meet this requirement, the construction of a 24-hour prognostic 500-mb. chart was made from 1500 GMT on the 13th, utilizing the vorticity integration technique presented by Fjørtoft [1]. Although the technique is tedious and lengthy, it has the advantage of objectivity. Essentially what is done is to determine the upper flow pattern and height changes 24 hours in the future, assuming that the absolute vorticity is conserved and moves with the direction and strength of the computed mean flow pattern. The method was followed exactly, except that 80 percent of the geostrophic wind was used in advecting the vorticity field, as recommended by Cressman [2]. The prognostic chart and the actual verification at 1500 GMT, February 14, are shown in figures 11 and 9. The merging of troughs in the center of the country, the change to zonal flow off the west coast, and the development of strong winds over the Gulf region are indicated quite well. The 24-hour height change patterns also show good agreement with respect to location and orientation. The eastward shift of height falls from southern Arizona to Texas is perhaps the most significant single feature. The forecasted trough through the western States is approximately 18 hours too fast. This error is due to marked change in mean flow pattern over the Pacific and perhaps in part to possible error of original analysis over the ocean. The forecasted "hang-back trough" over northern Mexico is an error possibly due to original analysis error over areas where data are lacking, and to location on the fringe area of computation.

COMPARISON WITH OTHER GULF CYCLONES

It was also of interest to compare this case with the rather extensive study of Gulf cyclones by Saucier [3] in 1949. Despite the unusual speed and depth of this particular cyclone the preceding conditions for formation which he describes apply here. In accordance with his findings, evidence of westward retrogression of high level mean trough patterns was present, and polar air had invaded the eastern United States prior to the development. Some difference enters during the period that the Low traveled across the Gulf. The polar outbreak accompanying movement of the storm was stronger than the outbreak preceding storm formation. The second principal difference was the complete breakdown of low index to the west of the storm's longitude. Nevertheless these variations should not be construed to contradict in any way the findings of Saucier since the storm itself is by no means a classic example of the usual northern Gulf cyclone.

CONCLUSIONS

The review of this storm situation brought forth an appreciation of the influence of rapid air motion in both distorting and intensifying the interaction of airmasses. The remarkable integration of a variety of motions in the higher atmosphere is not often so clearly defined as it was in this case. The ability of the Fjørtoft technique to anticipate this integration implies that in this particular case the translation of a vorticity field already set up 24 hours in advance played a major part in the outcome.

ACKNOWLEDGMENTS

To acknowledge all of the help received in the course of this study would involve a sizeable portion of Analysis Center and other Central Office personnel. Particular appreciation is due V. J. Oliver for his instructive comments during construction of the Fjørtoft prognostic charts and to A. K. Showalter for analysis and interpretation of the isentropic charts. We also wish to thank the District Forecasters at New Orleans and Miami for their helpful comments and supplementary analyses.

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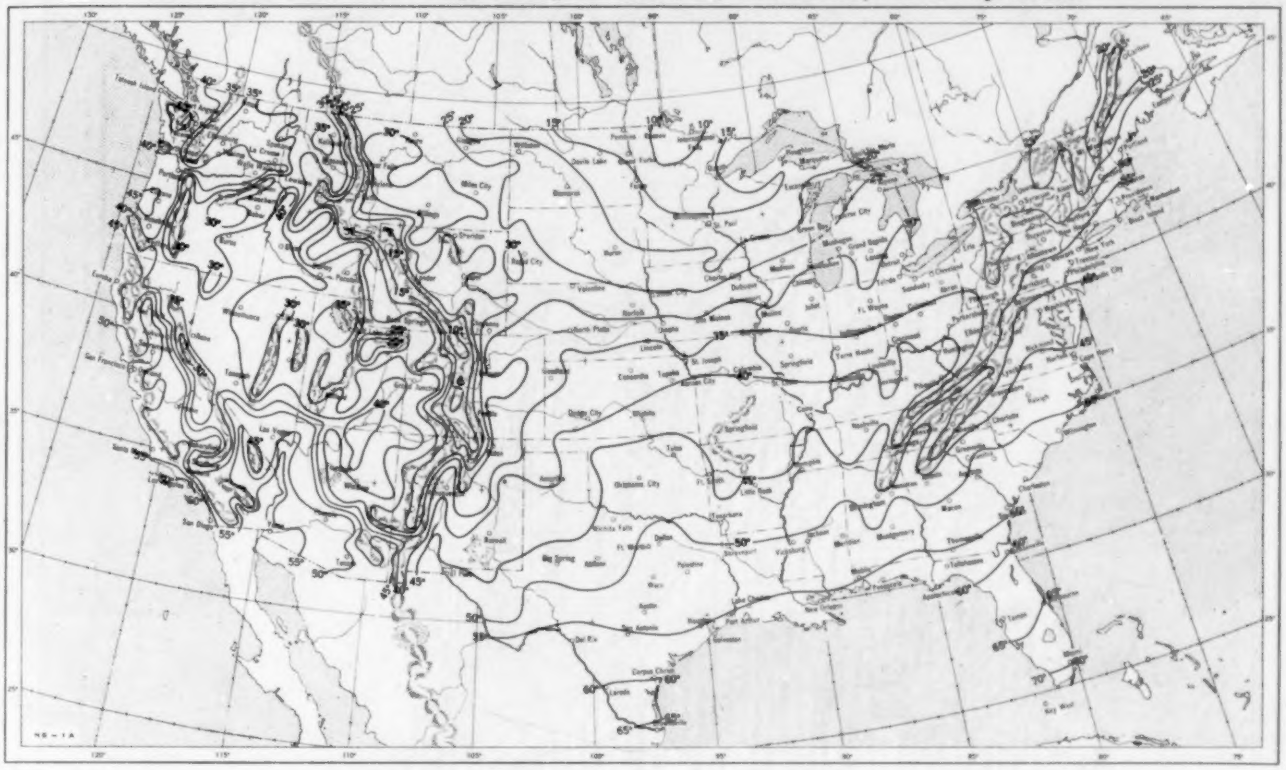
CORRECTION

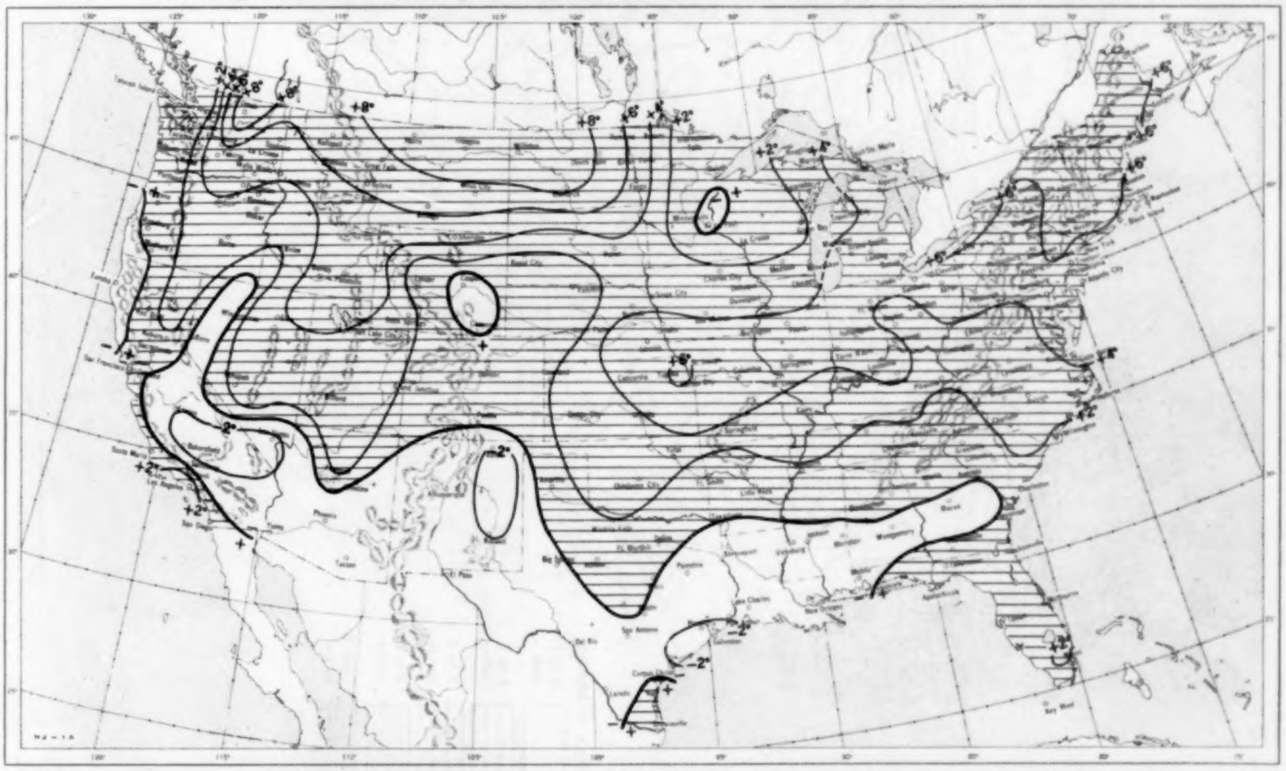
MONTHLY WEATHER REVIEW, vol. 80, No. 11, November 1952, p. 204: In footnote 3, ratio for making frequencies taken by 10° squares at 30° N. comparable to those taken at 40° N. should be cos 40°/cos 30°, *not* sin 30°/sin 40°.

U. S. GOVERNMENT PRINTING OFFICE: 1953

Chart I. A. Average Temperature (°F.) at Surface, February 1953.

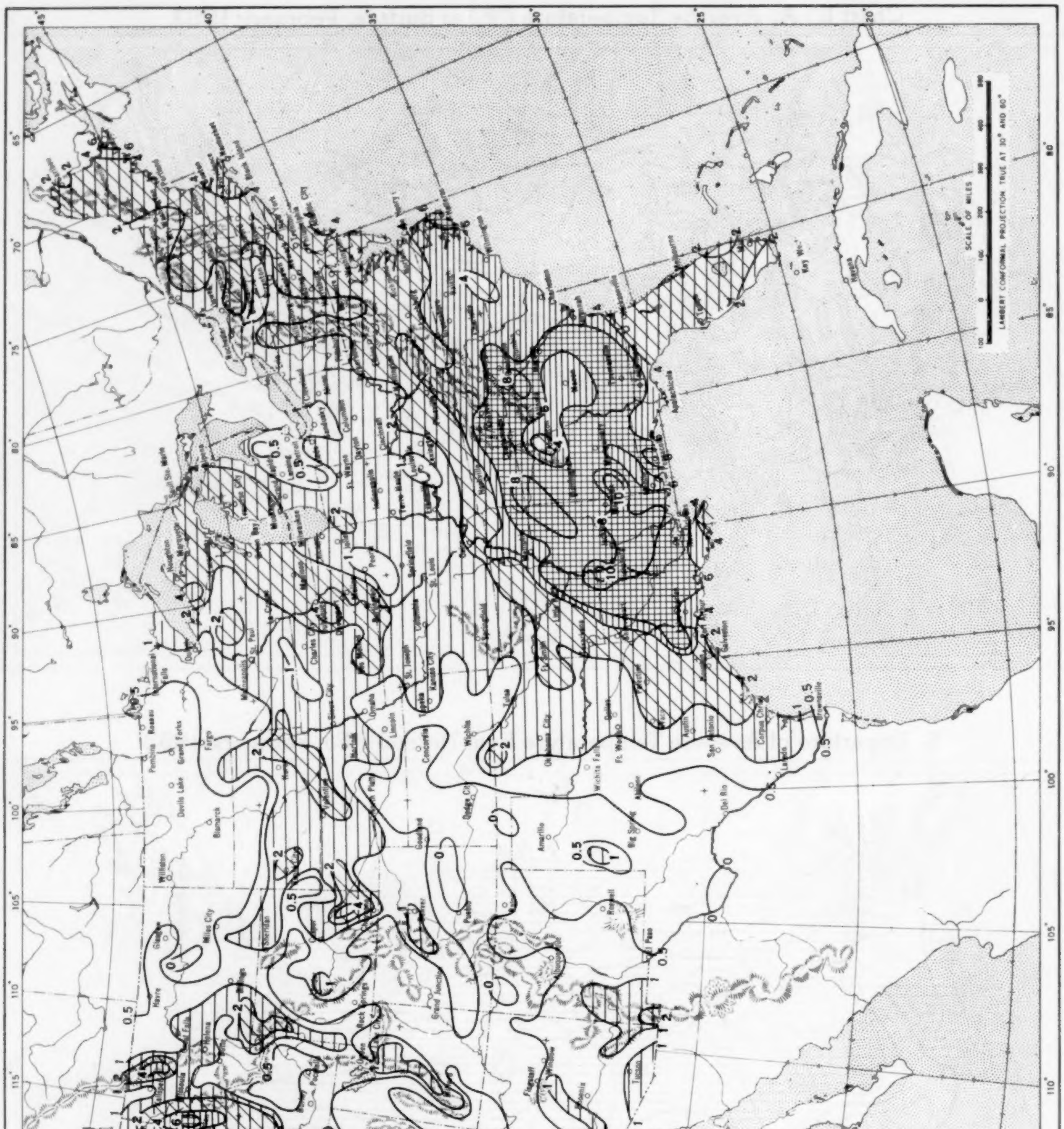


B. Departure of Average Temperature from Normal (°F.), February 1953.



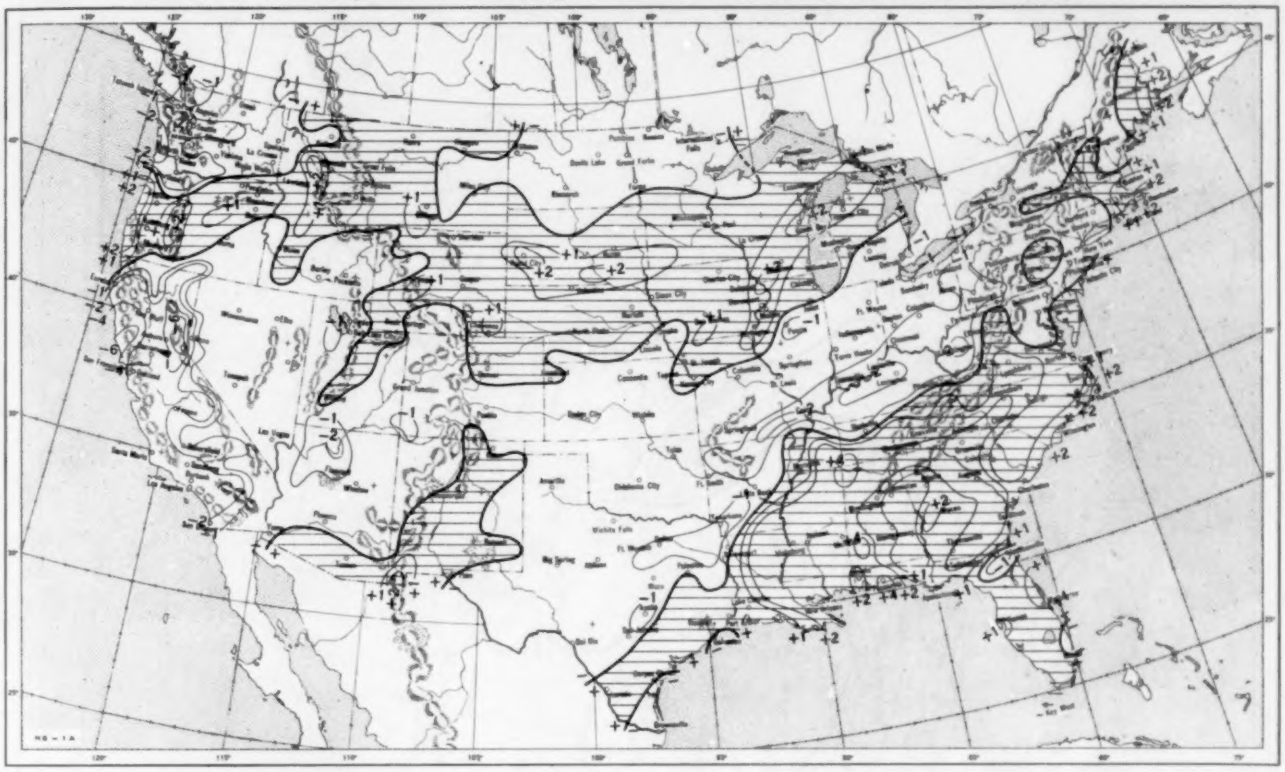
A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), February 1953.

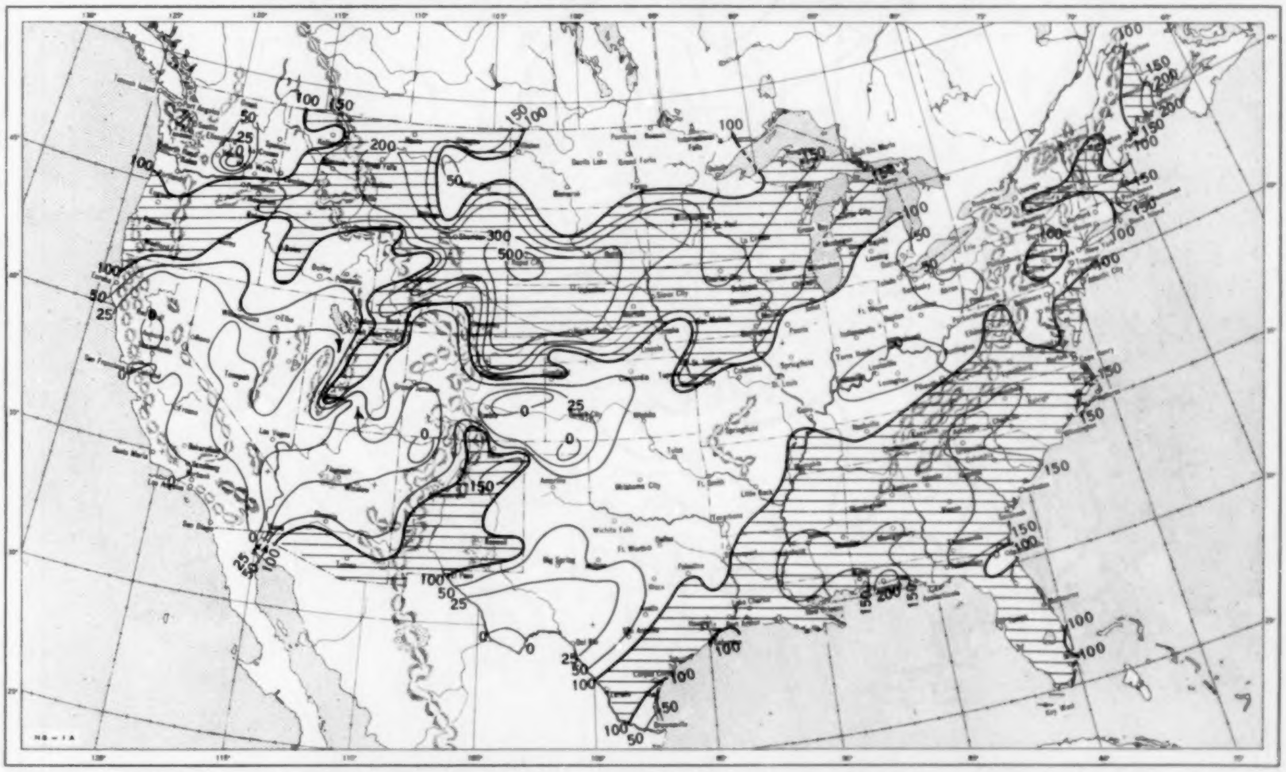


Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), February 1953.

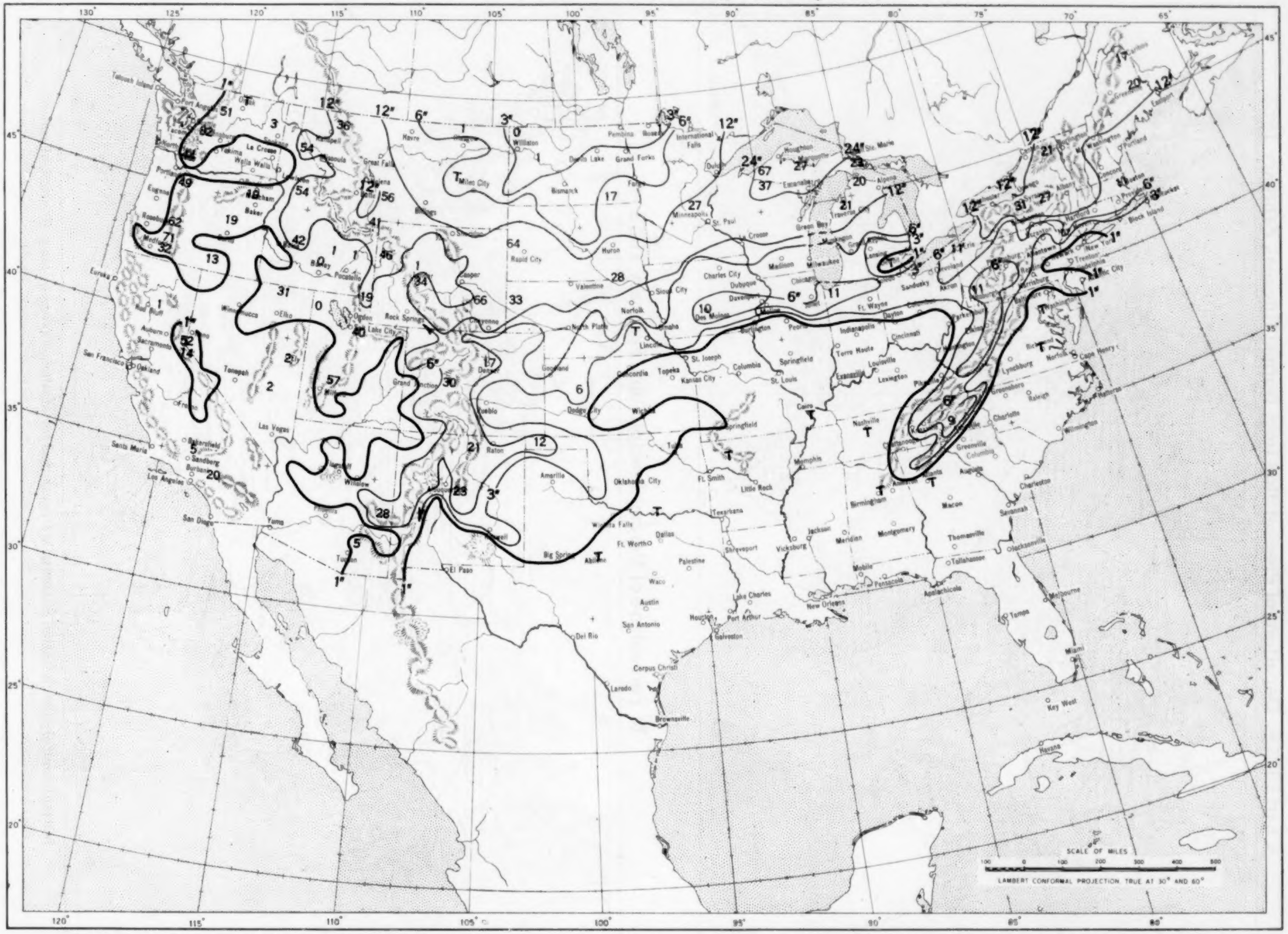


B. Percentage of Normal Precipitation, February 1953.



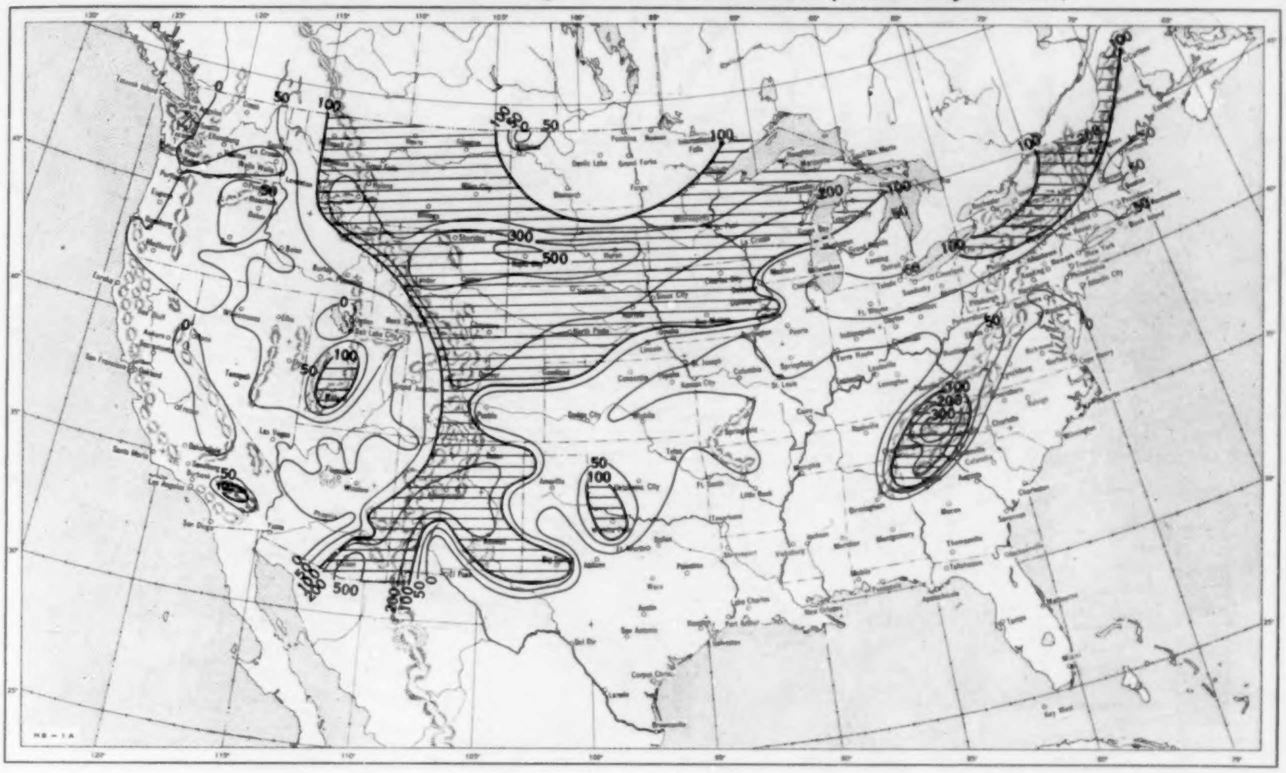
Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart IV. Total Snowfall (Inches), February 1953

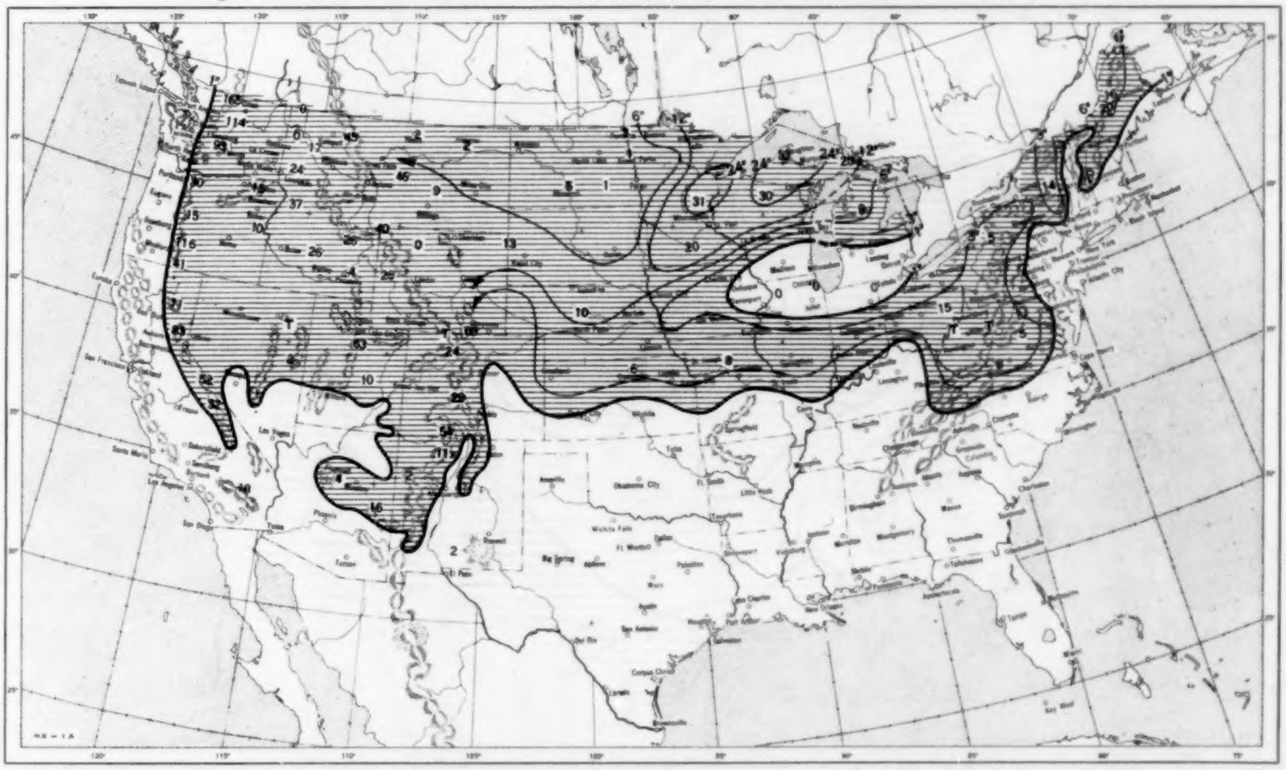


This is the total of unmelted snowfall recorded during the month at Weather Bureau and cooperative stations. This chart and Chart V are published only for the months of November through April although of course there is some snow at higher elevations, particularly in the far West, earlier and later in the year.

Chart V. A. Percentage of Normal Snowfall, February 1953.

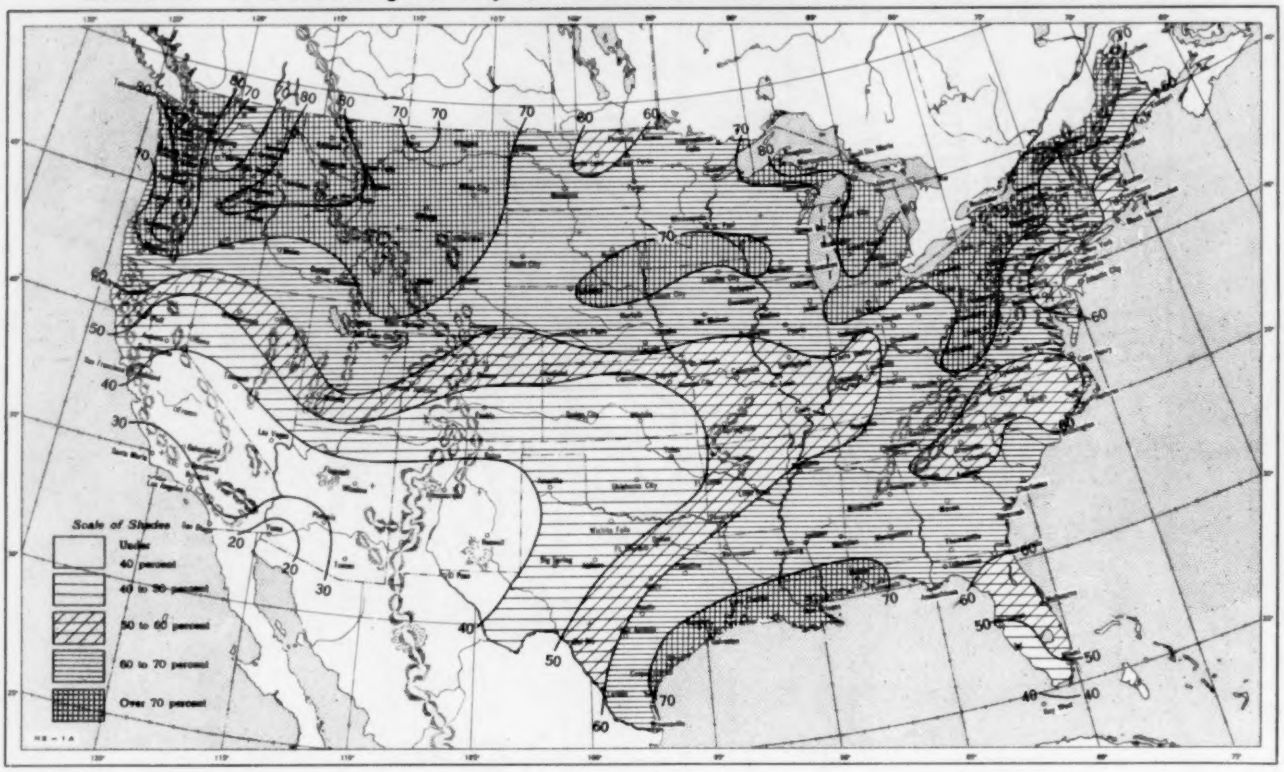


B. Depth of Snow on Ground (Inches), 7:30 a. m. E. S. T., February 24, 1953.

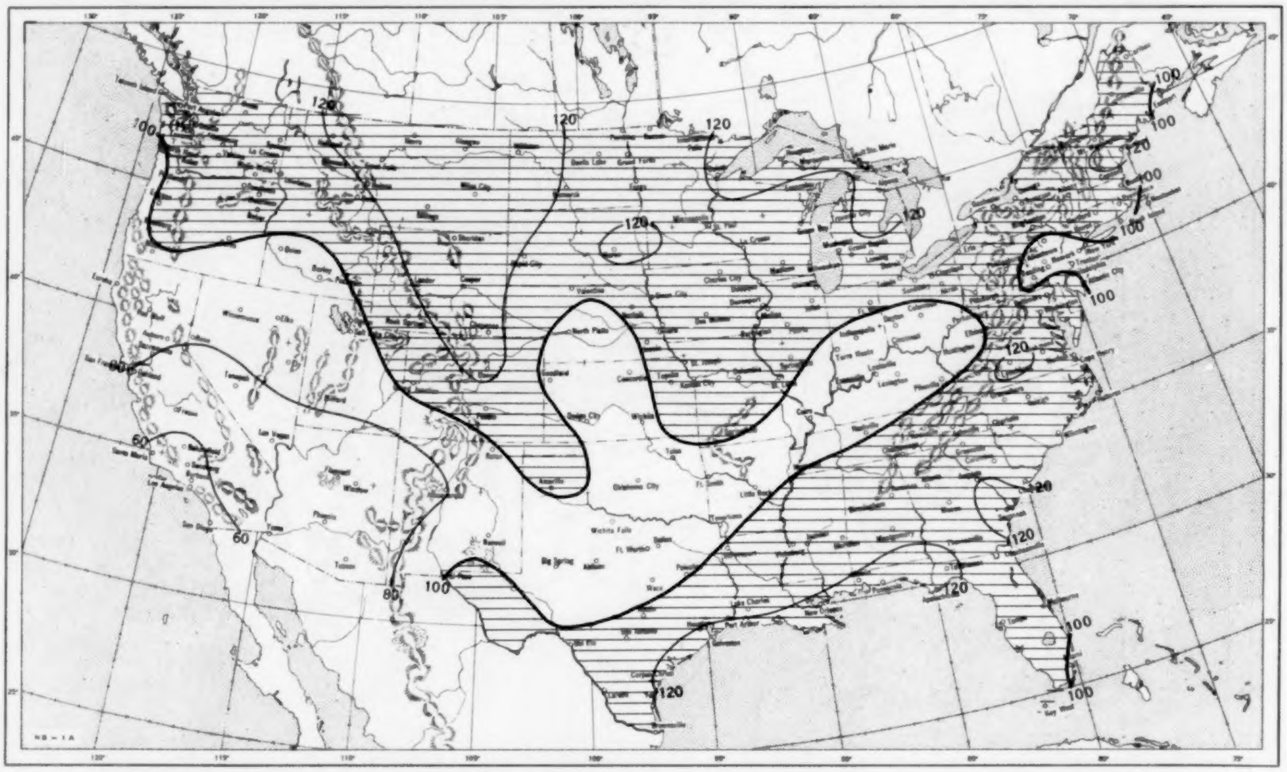


A. Amount of normal monthly snowfall is computed for Weather Bureau stations having at least 10 years of record.
B. Shows depth currently on ground at 7:30 a. m. E.S.T., of the Tuesday nearest the end of the month. It is based on reports from Weather Bureau and cooperative stations. Dashed line shows greatest southern extent of snowcover during month.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, February 1953.

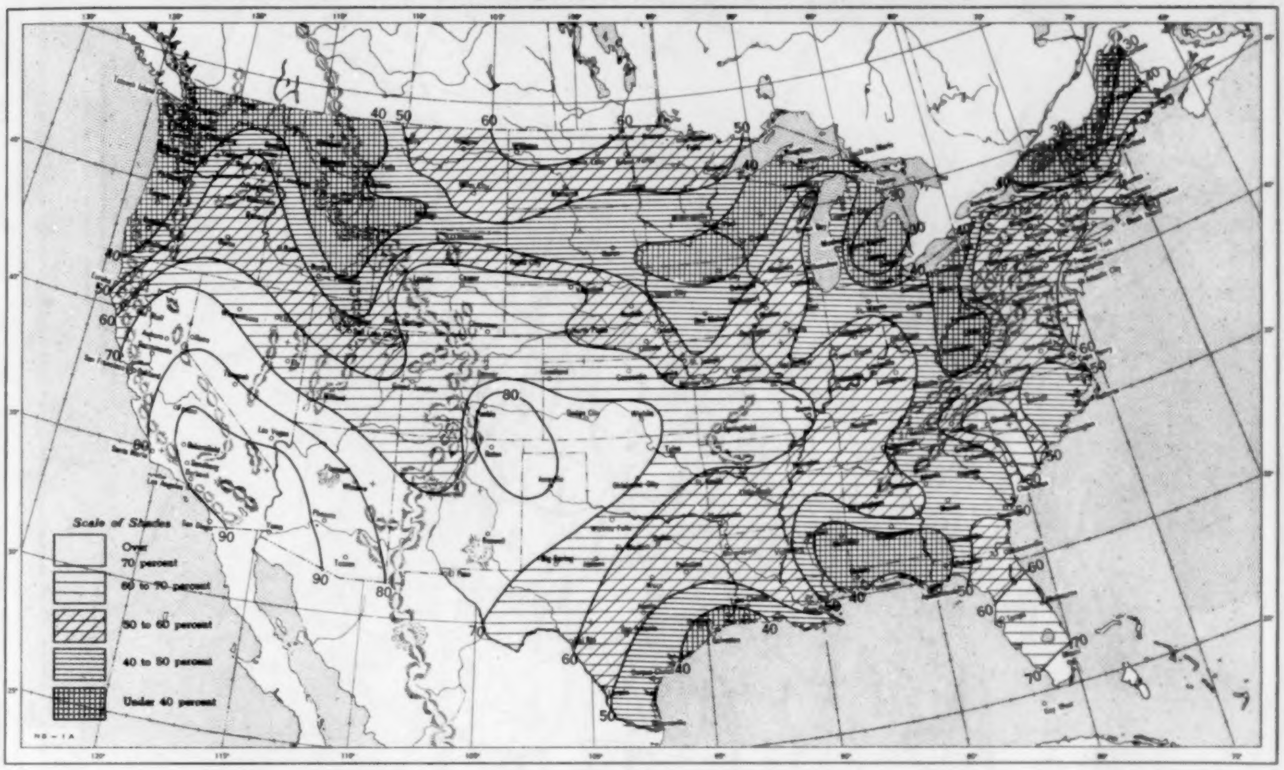


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, February 1953.

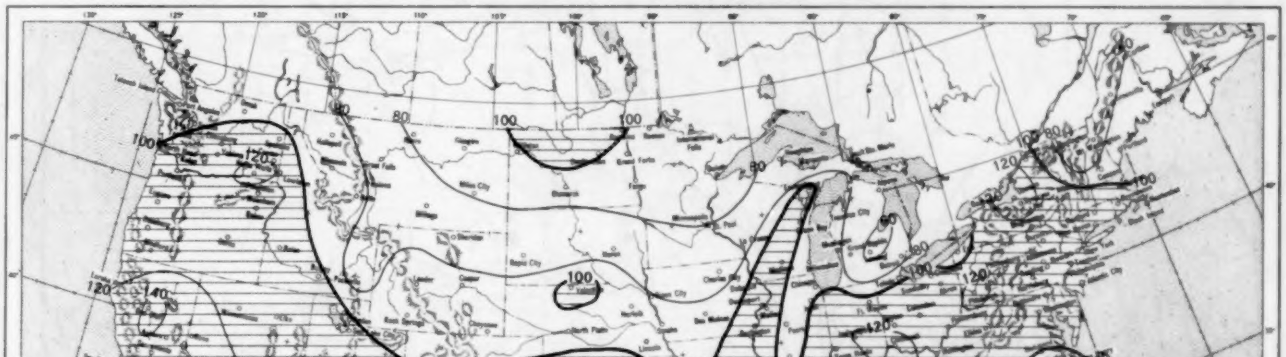


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, February 1953.



B. Percentage of Normal Sunshine, February 1953.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, February 1953. Inset: Percentage of Normal Average Daily Solar Radiation, February 1953.

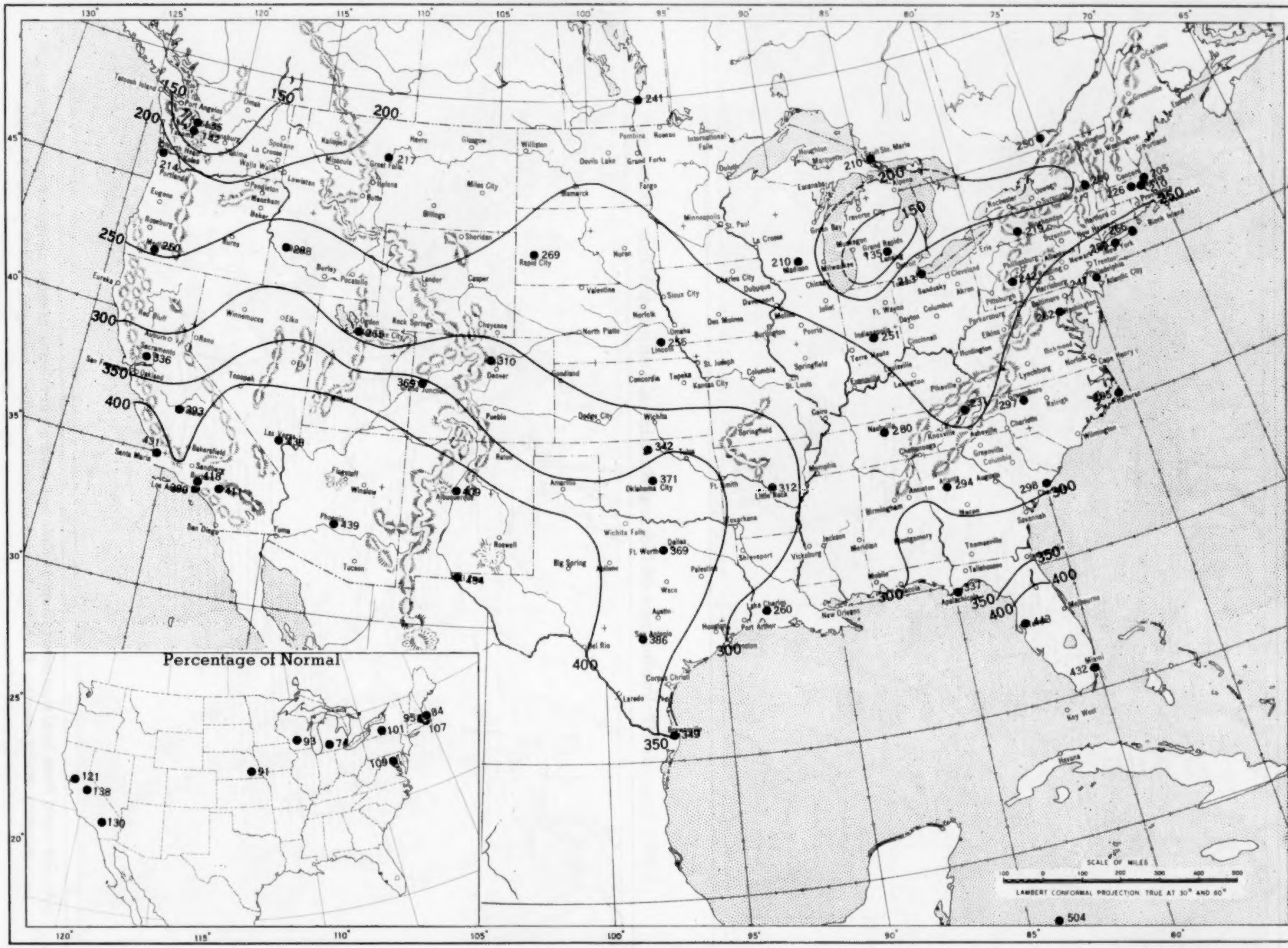
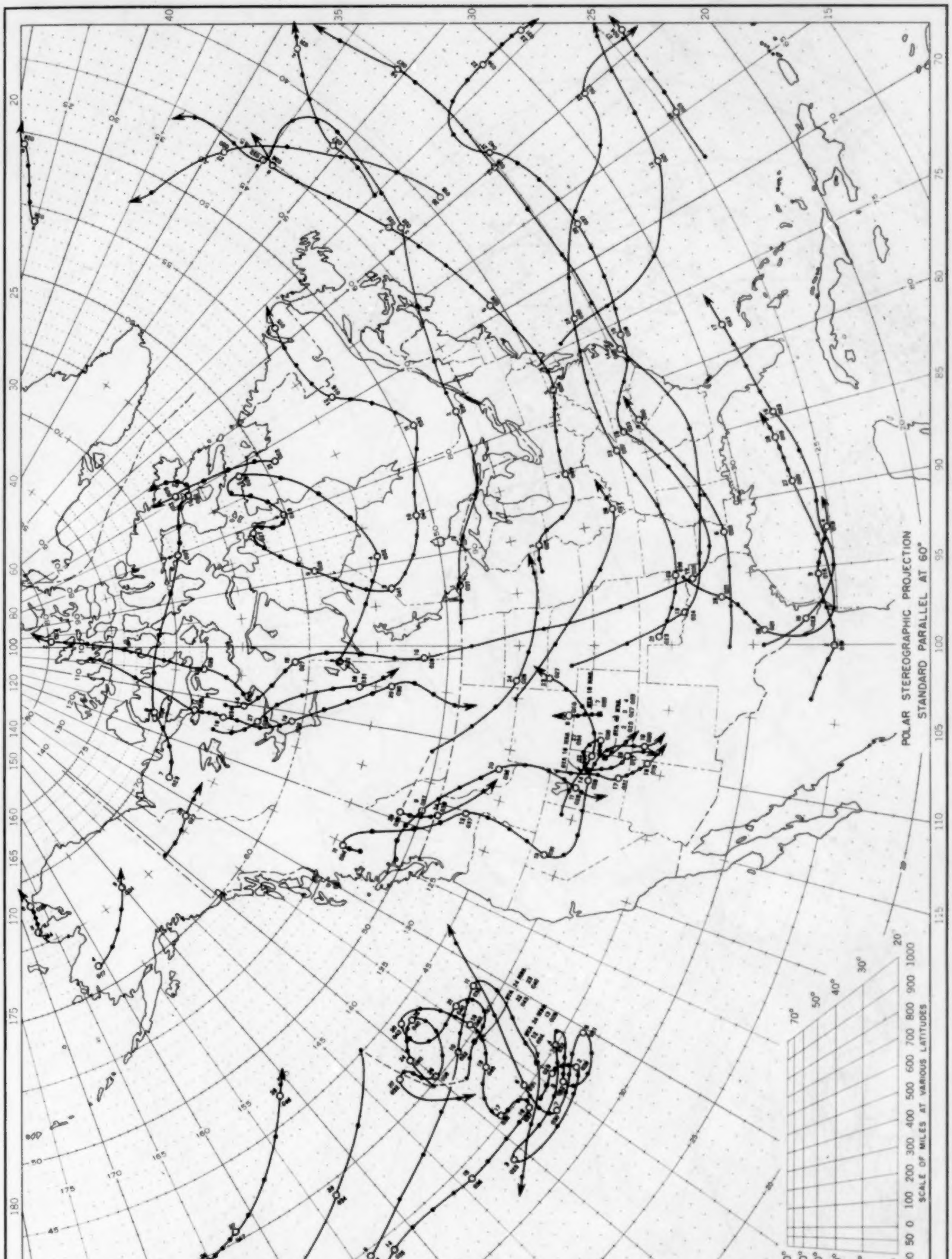


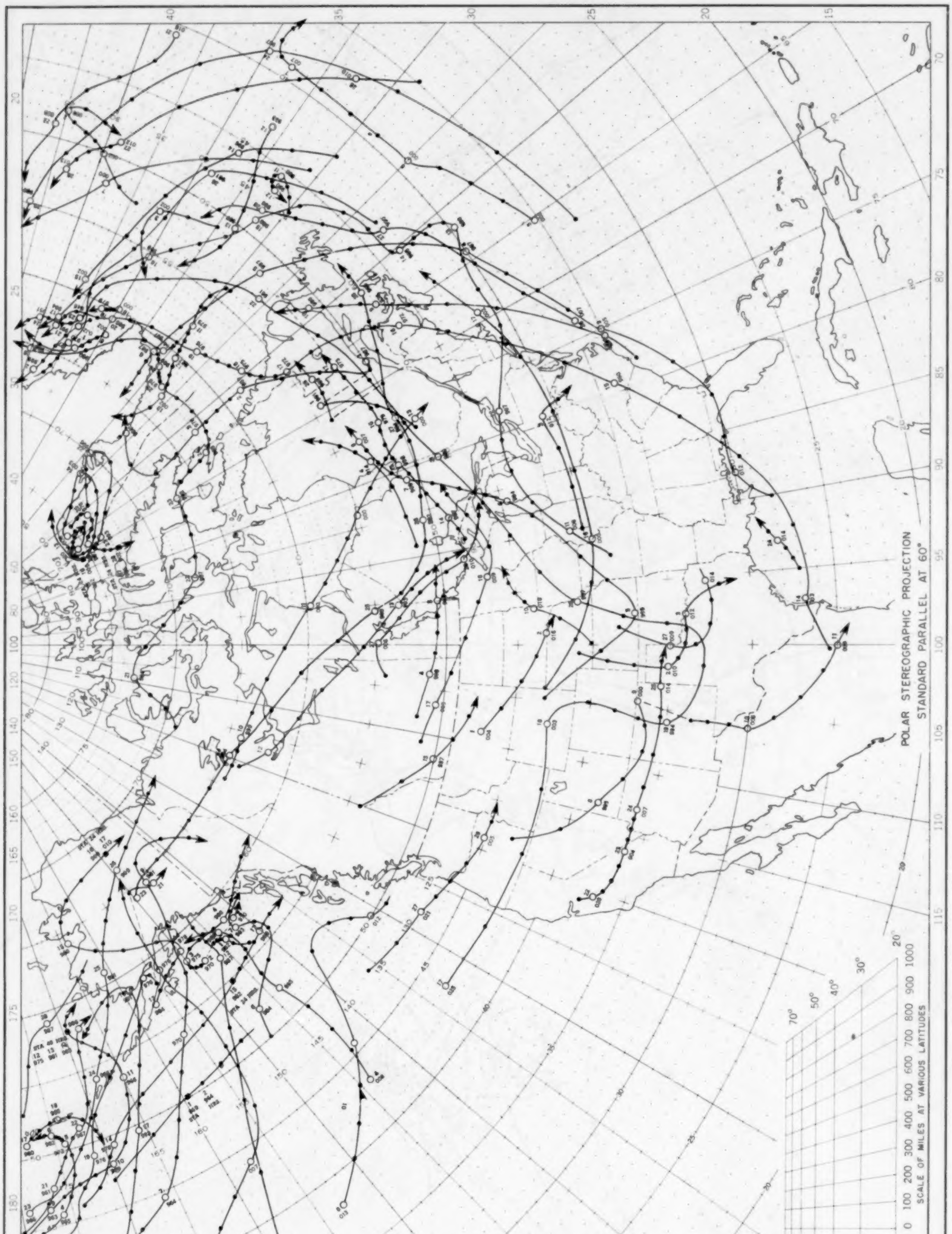
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown. Normals are computed for stations having at least 9 years of record.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, February 1953.



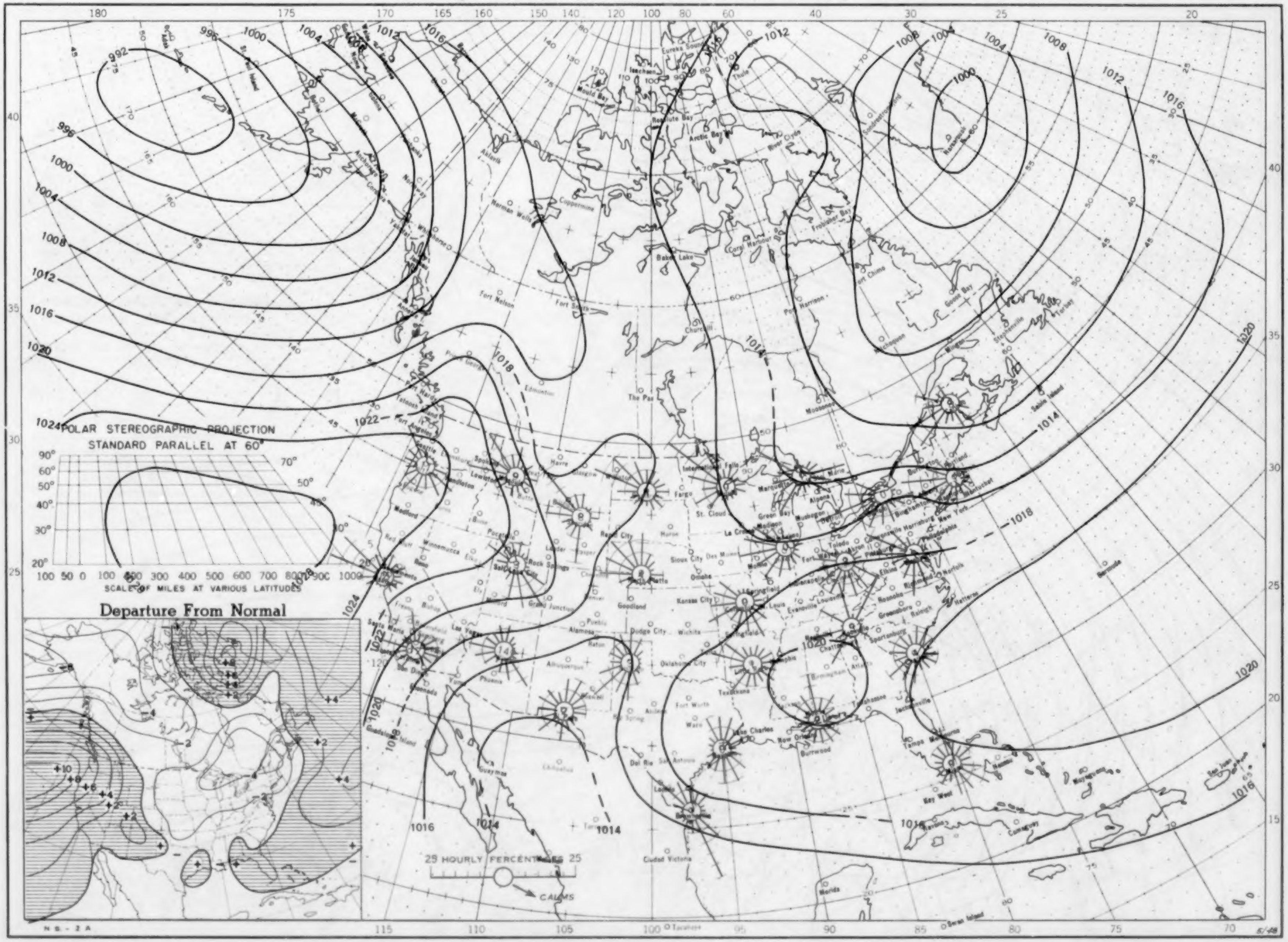
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, February 1953.



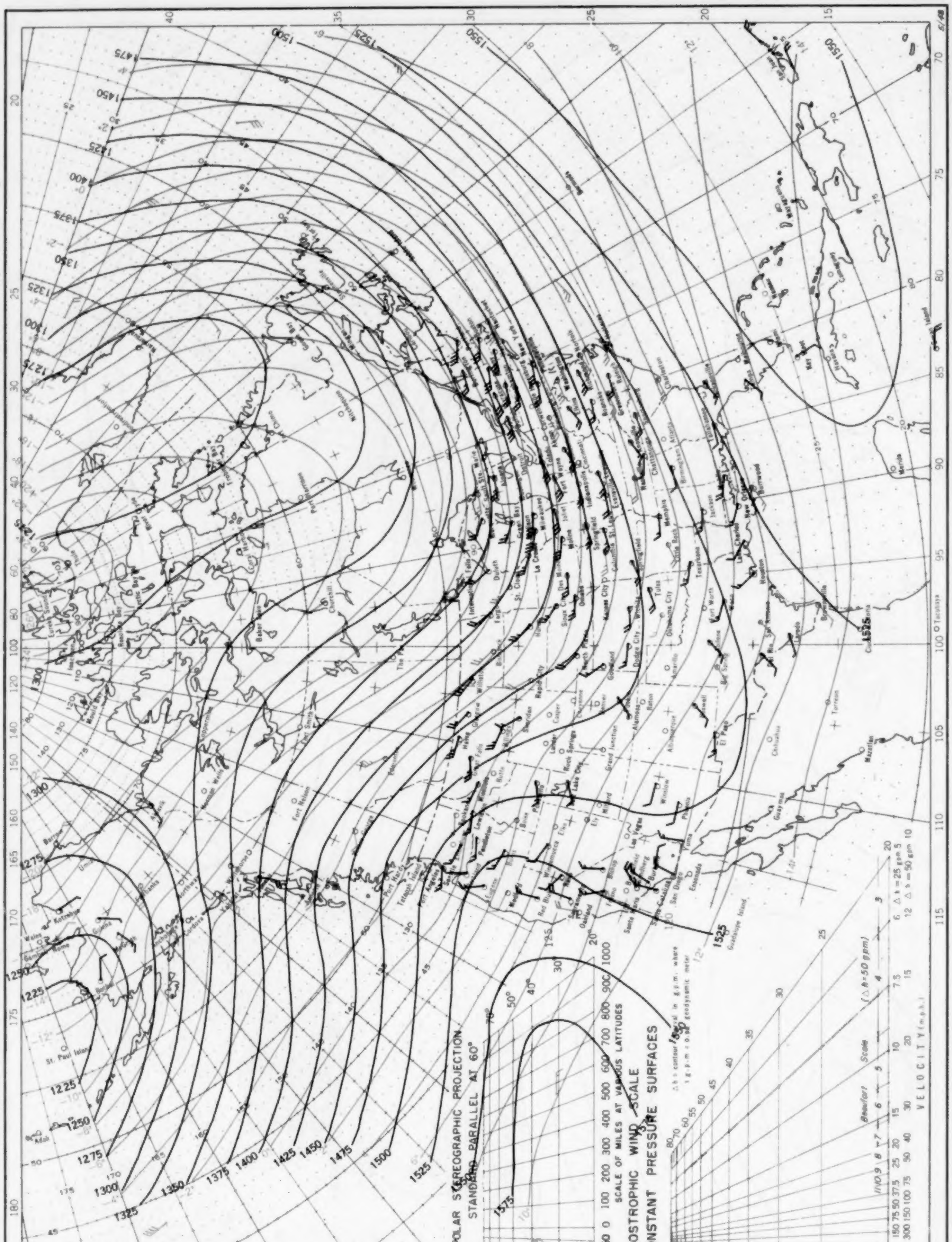
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, February 1953. Inset: Departure of Average Pressure (mb.) from Normal, February 1953.



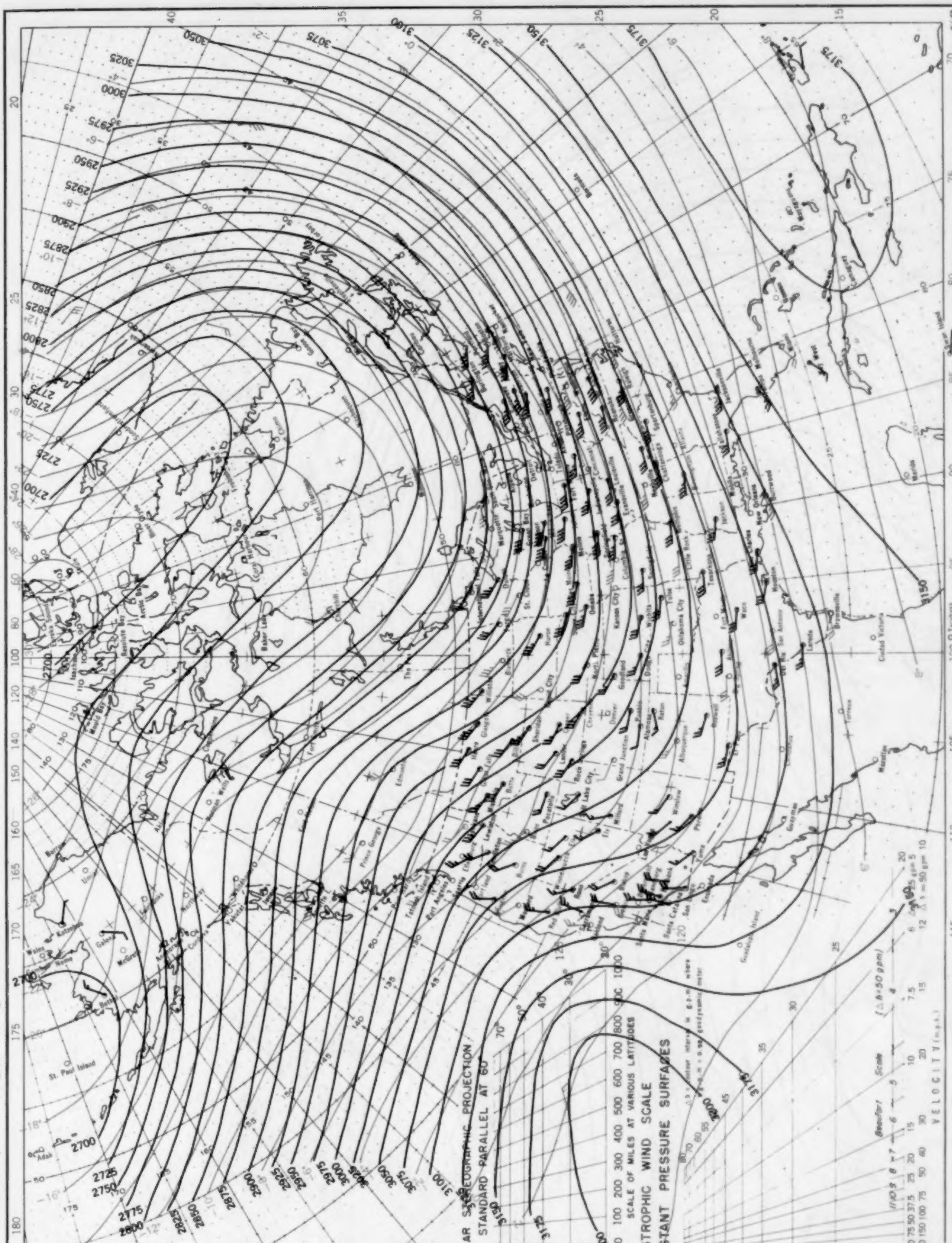
Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), February 1953.



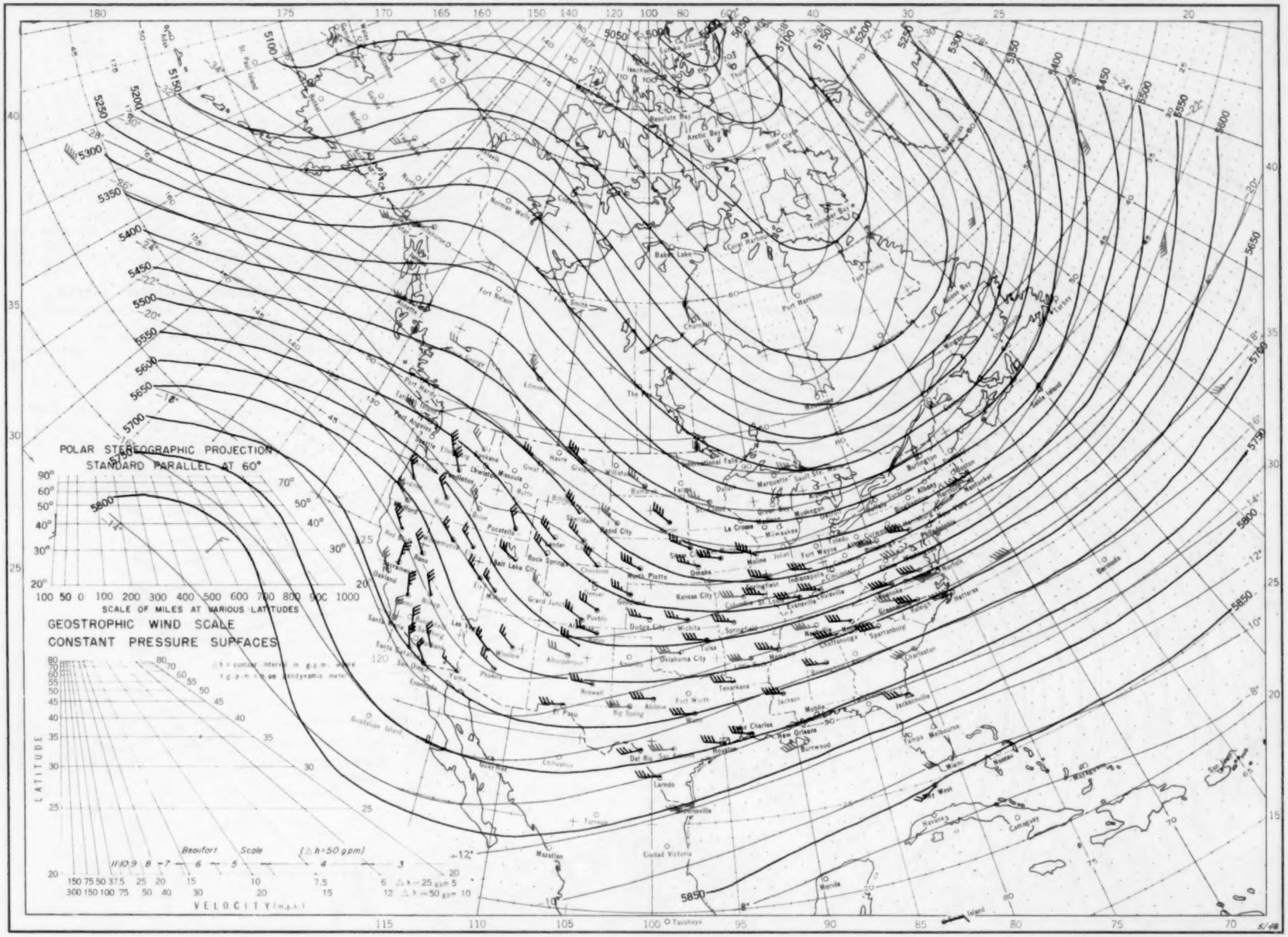
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), February 1953.



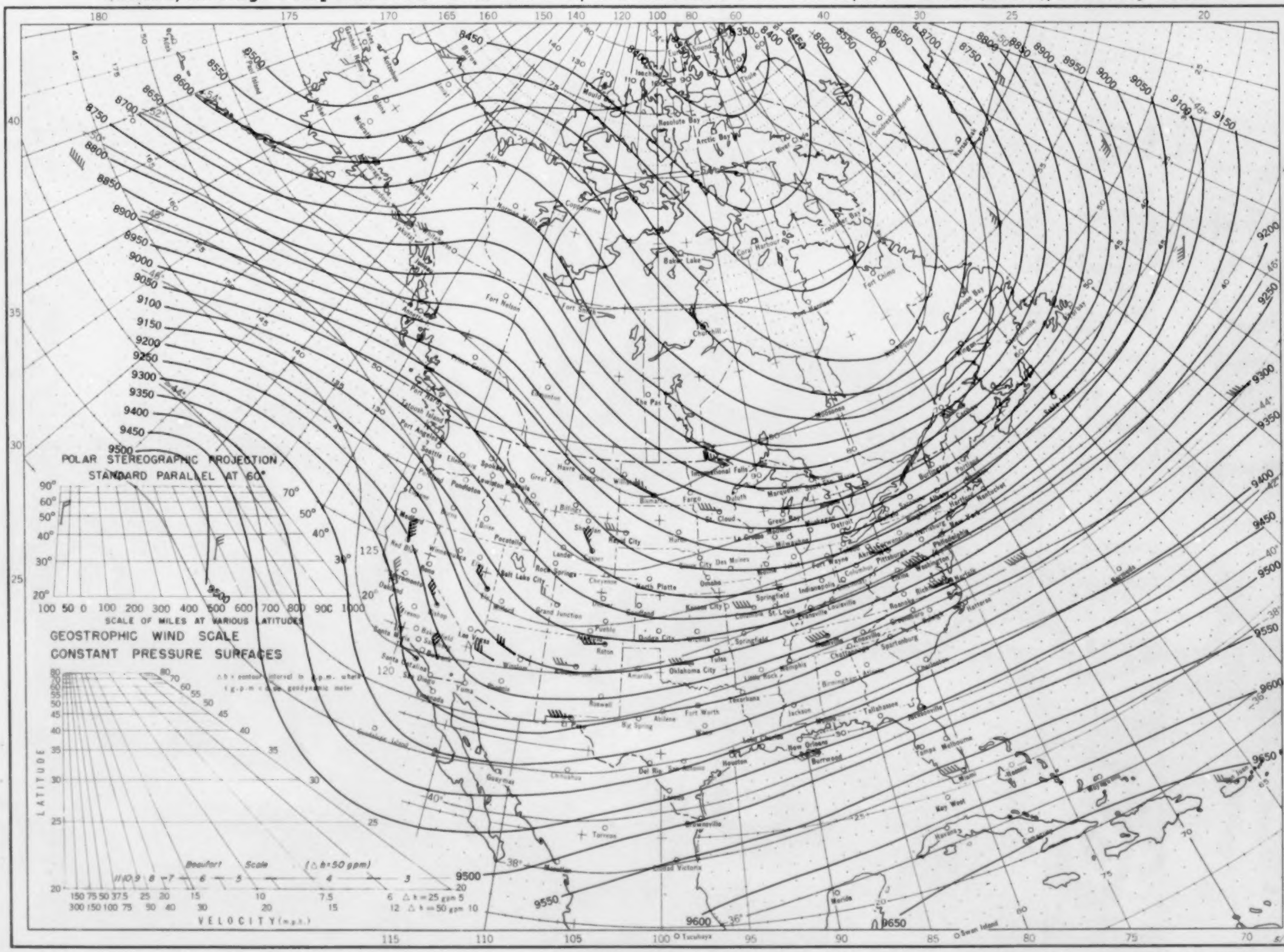
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C. at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), February 1953.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), February 1953.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.